On-site installation flexibility for disruption management in modular off-site construction systems

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DECLARATION

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except as declared in the Acknowledgements and specified in the text. It is not substantially the same as any work that has already been submitted before for any degree or other qualification except as declared in the Acknowledgements and specified in the text. It does not exceed the prescribed limit for the Engineering Degree Committee of 65,000 words, including appendices, footnotes, tables and equations, but excluding the bibliography, and 150 figures.

Brian Robertson

December 2020

I dedicate this thesis to my parents.

Abstract

Modular off-site construction is one of the methods adopted by the construction industry in a recent drive to modernise its operations and increase its productivity. Operations that were traditionally performed on-site are instead completed at an off-site factory, with finished modules then being transported on-site for installation. Operating across two locations in this way can provide numerous gains in speed, quality, and costs. However, it does mean that construction companies must now understand and manage a new and wider range of potential disruptions to their operations. This thesis is concerned with addressing disruptions that delay the delivery of modules to site.

To identify operational disruptions and their corresponding disruption management strategies, an exploratory study was performed consisting of five case studies and an industrial workshop. An over-reliance on storing modules as a means of coping with disruptions was uncovered. Construction sites typically follow a fixed module installation sequence because of on-site installation constraints. As such, when delivery of a module is delayed, subsequent modules in the sequence must be stored until the delayed module arrives for installation. As the industry expands towards manufacturing larger projects at higher production rates, storage may become a less viable disruption management strategy given the lack of storage space, particularly in urban areas. To overcome these challenges, a novel disruption management strategy is proposed and evaluated: *on-site installation flexibility*. There are four types: vertical assignment flexibility, lateral assignment flexibility, vertical sequence flexibility, and lateral sequence flexibility. Each type relaxes one of the on-site installation constraints, thereby allowing completed modules to continue to be installed in the event of a module being disrupted.

Several conclusions were drawn from studying on-site installation flexibility as a disruption management strategy. Implementation roadmaps developed during a workshop using an *Impact Matrix Cross-Reference Multiplication Applied to a Classification* analysis and *Interpretive Structural Modelling* revealed that implementing on-site installation flexibility requires coordination and many changes across a range of organisational functions. A *Discrete Event Simulation* model developed and applied to a case study showed that on-site installation flexibility can reduce installation delay and storage requirements. Furthermore, combining more than one type of on-site installation flexibility can significantly improve system performance. However, greater co-ordination effort would be required to control module installation operations. Finally, a *Simulation-Based Optimisation* model was formulated and applied to a second case study and showed that investing in a combination of on-site installation flexibilities in conjunction with other disruption management options can achieve cost savings. Hence, on-site installation flexibility was demonstrated to be a promising disruption management strategy for modular off-site construction systems.

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Chapter 1: Introduction

This thesis concerns disruption management in modular off-site construction. Operational disruptions and their corresponding disruption management strategies are investigated. To address shortcomings in the current strategies, a novel disruption management strategy of *on-site installation flexibility* is proposed. Implementation roadmaps for the different types of on-site installation flexibility are then devised. Finally, the behaviour and benefits of modular off-site construction systems enabled by on-site installation flexibility are investigated.

Note that the term *off-site construction* refers to the entire system involved in off-site construction projects, from the suppliers through to the construction site – not just the off-site factory.

1.1 Problem description and research motivation

Housing shortages are a problem faced in many regions across the globe including the UK (Miles and Whitehouse, 2013), Australia (Boyd, Khalfan and Maqsood, 2013), and China (Arif and Egbu, 2010). A range of reasons has been put forward to explain this deficit including population growth, lifestyle changes (Miles and Whitehouse, 2013), and labour shortages (Pan, Gibb and Dainty, 2007). Yet despite these shifts and growing demand, the construction industry has changed little in the past century: its processes and technology remain relatively the same – something which is in contrast with the manufacturing, logistics, and service industries (Blismas and Wakefield, 2009).

Off-site construction involves moving processes that were traditionally performed on-site to an off-site factory (Goodier and Gibb, 2007). Off-site construction has frequently been touted as part of the remedy to housing shortages (UK House of Commons, 2019) for a number of reasons including up to 60% reduction in project duration (Daniela and Miles, 2013), increased quality as a result of working in a controlled factory environment (Goodier and Gibb, 2005), and a more stable workforce permanently based at the fixed location of the factory rather than being hired locally for each new construction project (Pan, Gibb and Dainty, 2007).

One form of off-site construction is *modular off-site construction.* This involves manufacturing 3D volumetric units, which are typically the size of shipping containers, in an off-site factory. At the factory, modules are often fully fitted out with Mechanical, Electrical and Plumbing (MEP) systems, completed interior and exterior finishes, and in some cases furnished. Companies that were visited as part of this research produced such modules at the rate of about one per hour. Once modules are ready, they are transported to the construction site. At the site, the modules are installed according to a fixed sequence (Lee and Hyun, 2018). Consequently, should the delivery of a module to the site be delayed (e.g. because it must be held back at the factory as a result of component supply delay), all modules that succeed it in the installation sequence must be stored until the disruption has been resolved and the delayed module has been installed. Hence significant project delays and costs may be incurred by companies. In the future, disruptions are likely to be more challenging to manage for three reasons:

1. The production rate of modules is likely to increase as technological advances are made. Indeed, one of the companies interviewed as part of this study is intending to produce modules at a rate of one every ten minutes – a six-fold increase compared to the other factories that were visited. Consequently, any build-up of modules would happen in a much shorter space of time, giving companies much less time to react.
2. Disruptions that cause a delay are likely to be more frequent given a drive by the modular off-site construction industry to adopt lean manufacturing best-practices from the automotive industry such as Just-In-Time (JIT) and Just-In-Sequence (JIS) delivery (Linner and Bock, 2012). The off-site construction supply chain is still immature in many countries such as the UK (Miles and Whitehouse, 2013), and has not yet adjusted to the requirements of JIT and JIS production schedules. Such practices introduce a tighter coupling between the different elements in the supply chain and increase the risk of disruption (Wagner and Silveira-Camargos, 2011). Being lean comes at the cost of loss of flexibility which also exacerbates the risk of disruptions (Qamar, Hall and Collinson, 2018). Hence, when adopting lean practices, the modular off-site construction industry needs to find a way to maintain a certain level of flexibility to accommodate disruptions that can occur.
3. Project size (i.e. the number of modules per project) is expected to grow given the push to adopt modular off-site construction, particularly for high-rise buildings (UK House of Lords, 2018). Any long-lasting disruption to a module could result in a significant increase in the number of modules queuing up in storage. Furthermore, given the greater number of modules in a project, the greater the likelihood that at least one module is disrupted during a project.

Little research has been conducted to investigate such operational and managerial challenges in off-site construction (Hosseini *et al.*, 2018). It has been noted that more research is required to examine the risks of disruption that are faced by the modular off-site construction industry (Hwang, Shan and Looi, 2018) as well as disruption management strategies to address them (Li *et al.*, 2013). As a result, further research must also be carried out to develop approaches and methods to aid practitioners evaluate and select such strategies for modular off-site construction projects (Wuni, Shen and Mahmud, 2019). Ideally these strategies should be tailored to the modular off-site construction industry given that it has its own particularities (such as the unwieldiness of the container-sized modules) for which other strategies may not be as effective or as feasible to implement (Carvalho and Junior, 2015).

Thus, in this thesis the main operational disruptions and disruption management strategies currently faced by modular off-site construction companies are identified and their shortcomings analysed. Furthermore, a novel strategy of *on-site installation flexibility* is proposed and investigated as a way of reducing the reliance of modular off-site construction companies on using module storage as a disruption management strategy. On-site installation flexibility would allow the module installation sequence to be adjusted to take account of disruptions. One of the benefits of such an approach would be that even if the delivery of any module is delayed, installation at the site may continue rather than having to wait for the delayed module to arrive. This would therefore help to avoid any costly penalties being incurred by the company.

1.2 Research aim and research questions

In the previous section, several shortcomings in current modular off-site construction practice were identified. To address these shortcomings, the following research aim was defined:

Research aim: To investigate operational disruptions in modular off-site construction and identify, propose, and assess disruption management strategies to mitigate them.

Furthermore, the following four research questions (abbreviated as RQ1 to RQ4) are addressed in this thesis:

Research Question 1: What are the main operational disruptions faced by the modular off-site construction industry and how do companies currently cope with such disruptions?

Research Question 2: How can on-site installation flexibility be enabled?

Research Question 3: How can the appropriate level of on-site installation flexibility be selected to support effective disruption management?

Research Question 4: How does on-site installation flexibility affect the behaviour of modular off-site construction systems?

The first research question seeks to provide a better understanding of the disruptive environment in which modular off-site companies operate as well as how they currently cope with its challenges. The last three research questions are concerned with assessing a novel, flexibility-based approach to disruption management for the modular off-site construction industry.

1.3 Research approach

There are three fundamental aspects that underpin a research study (Corbetta, 2011; Yilmaz, 2013):

1. Ontological position: that is, what the researcher believes reality is.
2. Epistemological position: that is, what the researcher believes constitutes acceptable knowledge.
3. Research methodology: that is, the set of technical instruments that the researcher uses to acquire knowledge about reality.

Two central components of the theoretical grounding on which this research is built must be chosen: the ontology and the epistemology. With respect to the former, an *objective* view is adopted given the belief that entities exist externally and independently of the researcher (Saunders, Lewis and Thornhill, 2009). With respect to the latter, a *pragmatic* view is adopted because of the belief that the problem being studied is more important than the methods used. In other words, a researcher should not be limited to a single type of method to study a problem and should be able to draw on both qualitative and quantitative approaches (Creswell, 2009).

Research methodologies can be categorised into three groups: qualitative, quantitative, and mixed methods (Creswell, 2009). In line with the pragmatic view adopted by this research, a mixed method approach combining qualitative and quantitative elements was used. The reason for this choice was that a mixed-method approach leads to a better understanding of research problems (Creswell, 2009) because it combines the benefits of the different methods (Yilmaz, 2013).

On the one hand, qualitative research methods are well suited for research that is exploratory in nature (Creswell, 2009). They are appropriate for investigating phenomena that are little understood and for which the factors that influence them are unknown (Creswell, 2009). They are useful for obtaining in-depth understanding of the context and issues being studied by using open-ended questions without a pre-determined set of factors unduly influencing a subject’s response. Currently, little is known about the disruptions and disruption management strategies used by modular off-site construction companies. Furthermore, the concept of on-site installation flexibility for disruption management has only just been put forward in this thesis and hence there is no existing research on it. Qualitative methods are therefore an appropriate choice for some parts of this research.

On the other hand, quantitative research methods are primarily made up of mathematical techniques. These are useful in identifying the factors that strongly influence (or do not influence) the behaviour of observed phenomena and their utility (Creswell, 2009). Such methods can lead to a set of broad and generalisable findings. These methods are therefore well suited to investigating the behaviour of modular off-site construction systems when on-site installation flexibility is enabled and whether it is of benefit.

The mixed method approach, whereby quantitative and qualitative methods were used in phases (Creswell, 2009), was predominantly sequential. The research methodology devised to answer the research questions was divided into five phases, as shown in Figure 1-1. Where appropriate, each step in the diagram is shaded in yellow or blue to identify steps of the research that are primarily qualitative or quantitative, respectively. Figure 1-2 shows a detailed breakdown of the methodology. In both figures, *modular off-site construction* is abbreviated to *MOSC* for conciseness.

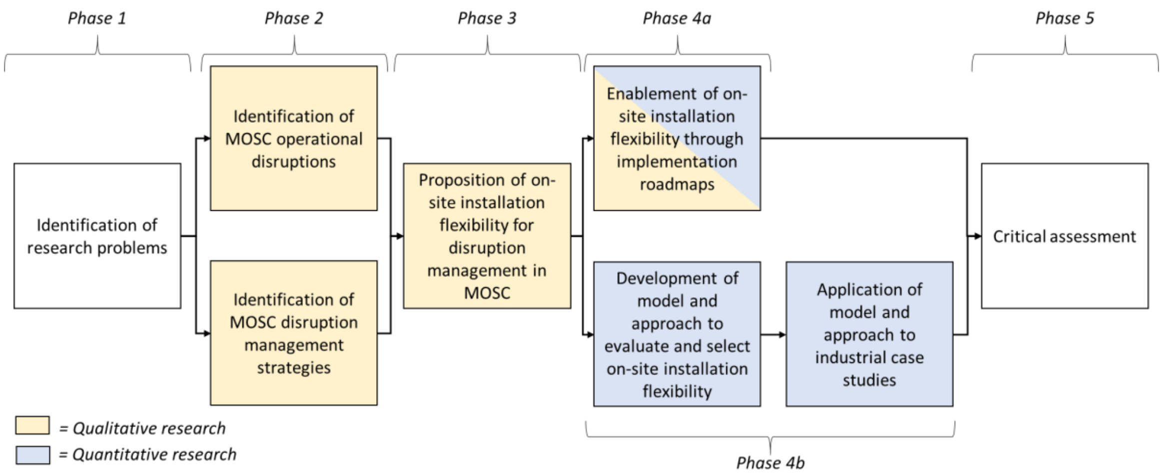

Figure 1-1: Overview of research methodology.

An overview of each phase of the methodology is given below. A more detailed justification for the choice of methods used in the various phases of the methodology is provided as appropriate in the chapters to come.

Phase 1: A review of the state of the art of off-site construction was undertaken. Furthermore, a review of literature in the four areas that are key to this research was conducted to gain a better understanding of: i) operational disruptions in modular off-site construction systems; ii) robustness of supply chains to disruptions; iii) disruption management strategies in modular off-site construction; and iv) methods to evaluate and select disruption management strategies. Where literature specific to modular off-site construction proved to be scarce, these four areas were considered in a broader context.

Phase 2: To address RQ1, a qualitative study including interviews, factory visits, and an industrial workshop was conducted. An analysis of the results pointed out the shortcomings in current disruption management practices used in the industry. These findings formed the basis for proposing a new approach to address certain operational disruptions in the modular off-site industry: on-site installation flexibility.

Phase 3: Four different types of on-site installation flexibility were proposed. The potential benefits of each were illustrated using hypothetical disruption scenarios.

Phase 4a: This phase of the research addressed RQ2. Through an industrial workshop, the key enablers of the different types of on-site installation flexibility were identified as well as their interdependencies. Implementation roadmaps for each flexibility type were then created using *Interpretive Structural Modelling* (ISM) and the interdependencies were further analysed using *Impact Matrix Cross-Reference Multiplication Applied to a Classification* (MICMAC) analysis.

Phase 4b: To address research questions RQ3 and RQ4, a quantitative model was needed to evaluate and select on-site installation flexibility. Following a discussion on potentially suitable methods, a two-stage *Simulation-Based Optimisation* (SBO) model was developed. The first stage is a *Discrete Event Simulation* (DES) used to model the behaviour of a modular off-site construction system. The second stage of the model is an *Integer Linear Program* (ILP) that selects the optimal combination of disruption management strategies to maximise cost savings. The SBO was incorporated into an approach to aid decision-makers to select the most appropriate level of on-site installation flexibility for disruption management. The DES was used to gain insight into the behaviour of a typical modular off-site construction system with on-site installation flexibility through a case study of a high-end residential apartment block project. The aforementioned approach was then validated in a case study on a social housing apartment block.

Phase 5: The final phase of the research consisted in a critical assessment of the findings. In doing so the contributions to both the academic body of knowledge as well as industrial practice were put forward. Furthermore, the limitations of the research were discussed and, in view of these, recommendations for future work were given.

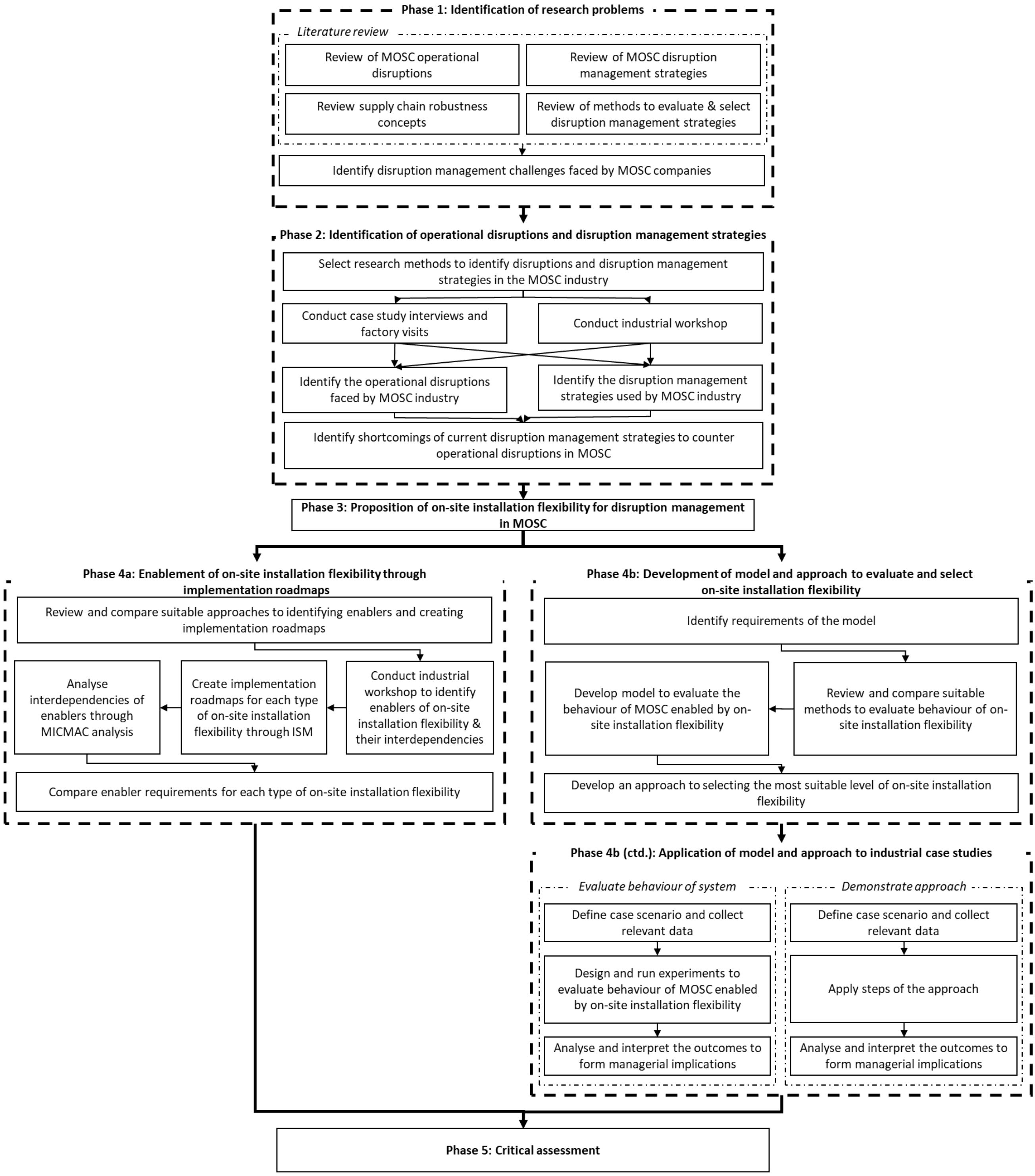

Figure 1-2: Research methodology. Modular off-site construction is abbreviated to *MOSC*.

1.4 Organisation of thesis

This thesis is divided into seven chapters as shown in Figure 1-3. The different phases of the research methodology identified in Figure 1-2 are mapped onto each chapter.

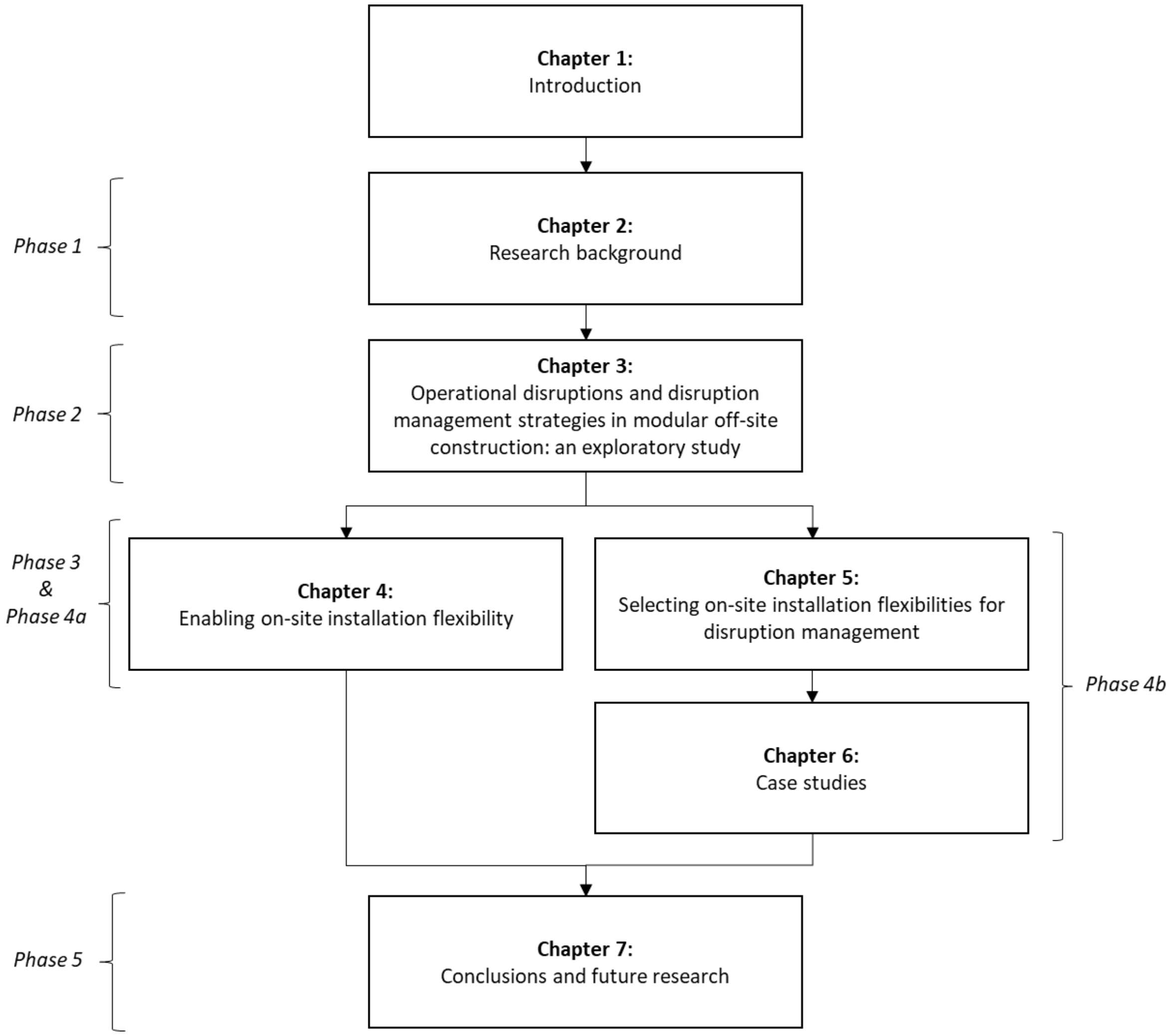

Figure 1-3: Organisation of the thesis.

Chapter 2: Research background

2.1 Introduction

This chapter has two aims:

1. To provide background information about modular off-site construction and supply chain robustness concepts.
2. To position this work in the existing body of research as well as justify the research gaps, research aim, and research questions that this thesis addresses.

This chapter commences with an introduction to modular off-site construction by describing the state of the art (Section 2.2) as well as providing an overview of a typical modular off-site construction system's characteristics (Section 2.3). A review of operational disruptions and disruption management in modular off-site construction is then presented (Section 2.4). Finally, the research gaps identified from the review are presented along with corresponding research questions in addition to the overall research aim (Section 2.5).

2.2 The state of the art of off-site construction

The (Building Research Establishment, 2009) reviewed the various forms of Modern Methods of Construction (MMC) which encompass "a range of processes and technologies which involve prefabrication, off-site assembly and various forms of supply chain specifications" and classified them into five distinct categories that are described in Table 2.1.

MMC are by and large concerned with using new technologies to shift work that is traditionally done on a construction site to a factory (Parliamentary Office of Science and Technology, 2003; Pan, Gibb and Dainty, 2007). This is commonly referred to as off-site manufacturing (Venables and Courtney, 2004) or off-site construction (Vokes *et al.*, 2013).

Table 2.1: Various forms of Modern Methods of Construction.

Modern Methods of Construction	Description
Volumetric off-site construction, which includes a) **modular off-site construction** and b) **off-site construction of a complete building**	There are two types of volumetric off-site construction: modular off-site construction and off-site construction of a complete building. The former involves modules, such as apartment rooms, that are manufactured off-site and subsequently transported on-site and fastened together to form buildings. These units may also have been fully fitted out within the factory (Kempton and Syms, 2009). The latter type is the most complete form of off-site construction where buildings are fully constructed off-site and then transported to the site to be installed on the foundations.
Panelised off-site construction	This involves planar units, such as steel frame wall sections, that are manufactured off-site and subsequently transported on-site where they are fastened together to form buildings. This category may be split into two further sub-categories: "open" and "closed" panel systems. The former incorporate purely the structural elements (Venables, Barlow and Gann, 2004), whereas the latter have elements such as their insulation and services installed at the factory (Kempton and Syms, 2009).
Hybrid off-site construction	These are systems that involve a combination of the two above methods.
Off-site manufactured sub-assemblies and components	This involves sub-assemblies or components, such as pre-assembled MEP, that are produced off-site and then incorporated into a building.
Non-off-site manufactured MMC	These are innovative on-site methods such as tunnel form systems (UK National Audit Office, 2005).

Off-site construction has existed for many thousands of years (e.g. the production of stone slabs used in pyramids) but was re-adopted after the Second World War when prefabricated buildings were widely used as part of the rebuilding effort (Vokes *et al.*, 2013). A diverse range of off-site construction methods, using an array of materials, has been used in many different markets throughout the world (IFM DIAL, 2016). In Europe, wooden panelised systems are dominant in densely forested regions such as Scandinavia and Germany whereas concrete and steel frames are the systems of choice in southern Europe. These primarily target the residential, commercial, and industrial market segments. In the UK, modular volumetric systems have been used in buildings for hospitality, education, and commerce. Japan uses the highest proportion of off-site construction in the world (Bendi *et al.*, 2012). There, the use of wooden panelised, steel frame, and concrete systems account for 80%, 15%, and 5% respectively of prefabricated buildings (Linner and Bock, 2012) and are primarily aimed at the residential market. In Australia, there is a mix of low and high rises that are predominantly made of modular systems for a wide range of markets from residential to healthcare. Panelised systems made of steel, concrete, and other materials such as uPVC (unplasticised polyvinylchloride) and PUF (polyurethane foam) are the most common in India where standardised single storey residential accommodation is the main application. That being said, in recent years India has seen significant investment in new off-site construction factories, most notably the KEF Infra One Industrial Park facilities at a cost of £73.61 million (KEF Holdings, 2016). In the Middle East, off-site methods are primarily panelised concrete systems for a range of target markets. In South America, the market is relatively unexploited but panelised systems (made of either concrete, polystyrene, gypsum or polyurethane) are the most common form of off-site construction and target the small single storey residential market. In contrast, mainland China has a growing off-site market and currently holds the record for the fastest building erected: 57 storeys in 19 days (Aberdein, 2015). The methods used are mainly multi-storey steel frame panelised systems destined for the residential and hospitality markets.

Despite the multitude of off-site products that exist throughout the world, the degree to which they are used differs greatly from region to region. Off-site methods account for a significant proportion of European housing markets: 15% in Germany (this is equivalent to approximately 20,000 houses per year), up to 33% in Austria, and 5% in France and Spain (Linner and Bock, 2012). The trend towards off-site construction is even more pronounced in Scandinavian countries such as Sweden, where 80% of detached family houses are produced using off-site methods (Duc, Forsythe and Orr, 2014). In Japan, between 13 to 15% of new houses are prefabricated. The largest Japanese producer of off-site housing, Sekisui House, produced 48,245 units between 2014-2015 (Sekisui House, 2016) while its all-time peak production was 78,275 units in 1997 (Linner and Bock, 2012). In the UK, off-site construction accounted for 6% of the housing market in 2011 (Pan and Sidwell, 2011) and had risen to 12-17% by the end of the decade (Construction Industry Training Board, 2019). In the USA, an estimated 3% of houses are built using off-site methods, although it is difficult to obtain an accurate figure because mobile homes are classified as off-site constructed housing (Duc, Forsythe and Orr, 2014). In many other regions of the world off-site construction is only beginning to be adopted.

To understand the potential reasons for the disparity in the rates of adoption of such techniques, one must consider the drivers and barriers for the use of off-site construction. On the one hand, there are many benefits that have been attributed to its use. A reduced construction time (see Figure 2-1) is frequently stated to be one of the main advantages of using off-site methods (Goodier and Gibb, 2005;

Pan, Gibb and Dainty, 2007; Kempton, 2009; Taylor, 2009; Miles and Whitehouse, 2013). For this reason, in countries such as the United Kingdom, which faces a significant housing shortage, off-site construction is seen as part of the solution to address this issue rapidly (Miles and Whitehouse, 2013). Indeed, construction could be sped up by up to 60% compared to traditional methods of construction and consequently financial benefits such as improved cash-flows may be achieved (Daniela and Miles, 2013). Furthermore, in a controlled factory environment it is possible to achieve high quality products with an 80% reduction in defect rate and so-called snagging, meaning construction problems (Goodier and Gibb, 2005; Pan, Gibb and Dainty, 2007; Taylor, 2009; Daniela and Miles, 2013; Miles and Whitehouse, 2013). Moreover, the concentration of labour in an off-site factory makes it more resilient to traditional construction skill shortages (Pan, Gibb and Dainty, 2007). Health and safety improvement is another major draw to off-site (Pan, Gibb and Dainty, 2007; Miles and Whitehouse, 2013), with the obvious human benefits and moreover a potential saving over traditional methods of construction of up to 80% in terms of financial cost due to injury (Daniela and Miles, 2013). What is more, off-site is claimed to be more eco-friendly for reasons such as waste reduction (Pan, Gibb and Dainty, 2007; Miles and Whitehouse, 2013).

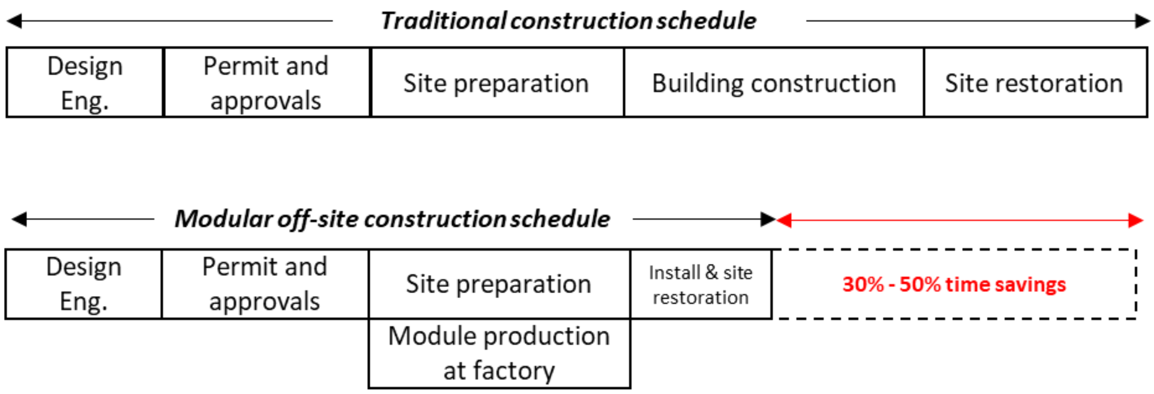

Figure 2-1: Modular construction schedule time savings adapted from (The Modular Building Institute, 2010)**.**

On the other hand, there are numerous inhibiting factors to the adoption of off-site methods. There is a perception that off-site is more expensive than traditional methods of construction (Blismas, Pasquire and Gibb, 2006; Goodier and Gibb, 2007; Kempton and Syms, 2009). However, it is also argued that the financial benefits that arise from better quality and health and safety are often overlooked (Goodier and Gibb, 2007). Industry surveys have produced conflicting reports as to whether (Nadim and Goulding, 2009) or not (Goodier and Gibb, 2007) off-site construction projects increase up-front costs. Furthermore, economies of scale may be difficult to achieve (Kempton and Syms, 2009) given that some market segments do not require mass production of buildings (Miles and Whitehouse, 2013) or where there may be a high level of customisation. Prefabricated buildings have a reputation for poor value and low quality because of those built in the post-war period (BRE Scotland, 2001; Calcutt, 2007; Goodier and Gibb, 2007). What is more, house builders are not always aware of the benefits of off-site methods (Goodier and Gibb, 2007; Miles and Whitehouse, 2013) and typically being risk averse, they will avoid the adoption of new technology unless there is a strong commercial incentive (Miles and Whitehouse, 2013). Moreover, the regulatory framework surrounding planning permission in some regions may not be suited to off-site construction methods and result in significant project delays (Pan, Gibb and Dainty, 2007).

The next section will describe the particular characteristics of *modular* off-site construction systems (from the suppliers through to the construction site), which this thesis focuses on.

2.3 Characteristics of modular off-site construction systems

The purpose of this section is to give the reader an overview of the structure and operations of typical modular off-site construction systems, where 3D modules are manufactured off-site and then transported on-site and fastened together to form buildings. Information from literature as well as insight obtained from factory visits (further detailed in Chapter 3) is presented. A general overview of modular off-site construction systems is first provided followed by more detail regarding the processes upstream of the factory, at the factory, and downstream of the factory.

2.3.1 General overview

Figure 2-2 shows the various entities that play a role in a typical modular off-site construction system, from the suppliers of raw material through to the construction site. Material transport heading downstream is represented by arrows. Flows heading upstream have been omitted for clarity.

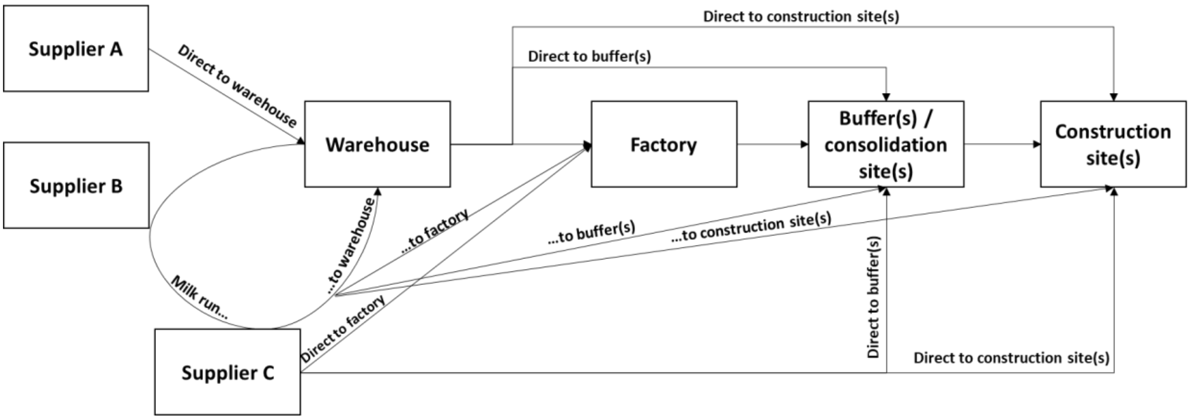

Figure 2-2: A typical modular off-site construction system adapted in part from (Miemczyk and Holweg, 2004)**.**

Figure 2-3 shows that a system can be defined according to two dimensions (Wikner and Rudberg, 2005): engineering and production. The engineering dimension ranges from fully engineer-to-order (ETO), where all designs are new for each customer order, to engineer-to-stock (ETS), where designs are already created and used as is for each customer order. The production dimension ranges from make-to-order (MTO), where products are only produced once an order has been received, to make-to-stock (MTS), where the product is entirely made prior to receiving an order. Systems may be defined anywhere in between the two extremes of each dimension. For example, some parts of designs could be MTS and the others ETO. The modular off-site construction industry is typically an MTO system in terms of the production dimension but can be anywhere along the engineering dimension. For example, a bathroom module could have already had its structure designed but the interior finish such as its tiling is engineered according to the customer's specification.

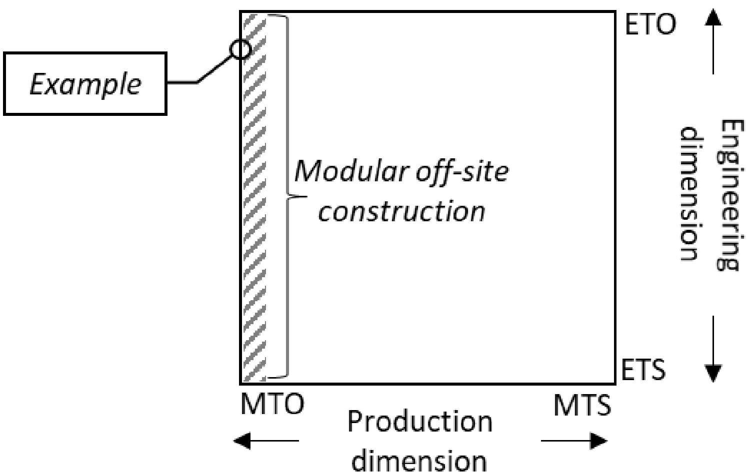

Figure 2-3: The two dimensions of production systems, adapted from (Wikner and Rudberg, 2005)**.**

2.3.2 Upstream of the factory

Figure 2-2 shows there are two main aspects that must be considered upstream of the factory: the suppliers and the logistic processes including the warehouse.

For a modular off-site construction company to be successful it is indispensable to develop a consolidated supply chain with a reduced number of suppliers by fostering long-term relationships with preferred suppliers. This is a challenge for the modular off-site construction industry because no two projects are the same and so nor are their supply bases. This makes it more difficult to achieve economies of scale, since large and regular orders are necessary to gain the cost benefits of factory-based production (Taylor, 2009).

Many existing suppliers of construction projects are small companies that primarily work in their local area. Indeed, 96% of the circa 250,000 construction companies employ fewer than 14 people (Office for National Statistics, 2015). Many of them are not familiar with supplying factories and do not have experience with JIT and JIS delivery.

Numerous logistics processes go on between the suppliers and the factory production line (Boysen *et al.*, 2015). Except for only a few parts that may be sent directly from suppliers to buffer/consolidation sites or the construction site, the majority will typically go to a warehouse. This warehouse may be either located at the factory itself or in close proximity.

2.3.3 The factory itself

The aim of this section is to define the characteristics of typical modular off-site construction factories. At the factory, as well as being put together, the modules are often fully fitted out with MEP (Mechanical, Electrical and Plumbing) systems. The extent to which the interior and exterior finishes are completed is dependent on the company. In some cases, modules are fully furnished at the factory and exterior cladding is attached, whereas in others these tasks are completed at the construction site. Figure 2-4 shows an illustration of the stage-by-stage assembly of a module. The size of the modules is constrained by what can be accommodated by the transport route from the factory to the construction site (Hwang, Shan and Looi, 2018). It has been observed that the production system is dependent on the configuration of the modules manufactured. Even when producing similar module configurations, there may be stark differences between the approaches used.

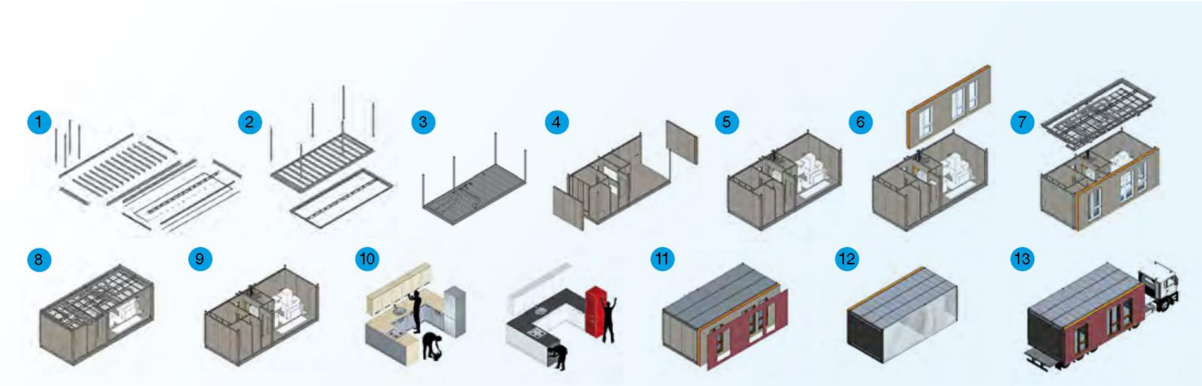

Figure 2-4: Various stages of a module assembly process at Laing O'Rourke (Laing O'Rourke, 2016)**.**

Legend: 1) Sub-assembly 2) Geo framing 3) Pipework installed 4) Internal wall installed 5) Kitchen loose install 6) External performance wall lowered over posts 7) Ceiling cassette install 8) MEP connected between ceiling and walls 9) Fix kitchen and bathroom 10) Final fit-out of kitchen and bathroom 11) Inspection and test 12) Temporary weather protection added 13) Load and ship to storage area.

One of the most apparent differences is the extent to which automation is utilised (Venables and Courtney, 2004). Some companies make very little use of automation. Their work is therefore highly labour intensive. The predominant use of skilled craftsmen is a defining aspect of the current modular off-site construction industry, which employs carpenters, plumbers, electricians, welders, etc. (Nasirian *et al.*, 2019). Consequently, certain factories resemble much more a construction site within a large covered area than a factory with an automated production line. Such enterprises limit themselves to producing around 8 modules per day – a takt time of about 1 hour – and it is questionable whether the rate of production could be increased much further without the use of automation or increased floor space and manpower. At the other end of the spectrum there are companies that make high use of automation for operations such as the production of a module's framework. Automation can streamline the operations but few companies go so far as flow line production as in the automotive industry (Linner and Bock, 2012).

A unique characteristic of the production in modular off-site factories is the size of the work in progress, be it modules or components to be fitted into the products (Blismas, 2007). The shipping-container-sized modules occupy a large amount of space on the already highly constrained shop floor. Should one of the modules on the factory floor be delayed, it is not possible to extract it to allow other modules to overtake, which may cause a significant disruption to the overall production. Hence it is vital to ensure the resilience of the modular off-site production system.

The way production is scheduled is also different to most industries. Companies have an incentive to produce modules according to the fixed module on-site installation sequence (Lee and Hyun, 2018). Doing so means that modules do not need to be re-sequenced according to the installation sequence.

However, this may conflict with certain factory processes where economies of scale may be achieved by, say, producing similar parts in a batch (Matt, Dallasega and Rauch, 2014).

2.3.4 Downstream of the factory

Downstream of the factory there are three main entities: the logistics from the factory, the buffer (or consolidation site) and the construction site.

The downstream logistics from the factory are complex given the large size of the modules. The majority are subject to large-load transport restrictions during the day in urban areas and require specialist escort vehicles to accompany them.

The buffer is an intermediary area where modules may be delivered prior to their delivery to the construction site. It serves three main purposes:

1. Re-sequencing of modules: as mentioned previously, modules may come off the production line in a different sequence from the fixed module on-site installation sequence. Should the factory not have room to store and re-sequence the modules according to their on-site installation sequence, it is done at the buffer instead.
2. Buffering against any downstream on-site delays owing to, for example, inclement weather that may mean that modules cannot be hoisted into position and have to be stored.
3. Storing modules that are later in the module on-site installation sequence and waiting for an earlier module that has been held back because of an upstream disruption.

Three concepts that are needed to discuss the on-site installation operations are defined next.

Definition 1: A slot
Is a location in a building where a module is to be installed.

Definition 2: Module installation sequence
Is the order in which modules are installed in a building.

Definition 3: Slot installation sequence
Is the order in which slots are filled with modules (e.g. Slot 1, then Slot 6, then Slot 2).

At the construction site, especially in dense cities such as London, there is very little space for storage of off-site products, particularly modular ones. As such, modules are delivered Just-In-Sequence to be hoisted into position by high load-bearing capacity cranes following the fixed module on-site installation sequence (Lee and Hyun, 2018). This sequence is fixed because of four on-site installation constraints, which are defined next.

Definition 4: On-site installation constraints

Four constraints restrict the choice of the slots in which modules are installed in a building as well as the slot installation sequence. A consequence of these is that the module installation sequence is therefore also fixed.

Constraint 1: Each module is assigned to be installed on a particular floor.

Constraint 2: Each module is assigned to be installed in a particular slot on that floor.

Constraint 3: Module installation on an upper floor may not commence until the floor below has been completed.

Constraint 4: The sequence in which slots on each floor have modules installed in them is fixed.

It is essential for the upstream processes to keep to schedule and deliver modules to the site on time to avoid significant extra costs for running the site and delay penalties.

2.3.5 Summary

Modular off-site construction companies typically operate a MTO production system and, depending on client needs, can produce a range of products from off-the-shelf ETS products to ETO products. Modular off-site construction companies struggle to establish a stable supply base that can meet their JIT requirements because no two projects are the same and the construction industry is highly fragmented. Logistics upstream of the factory are common to those found in other industries. However, the logistics of transporting modules downstream of the factory is much more complex given transport restrictions as well as the requirement for escort vehicles. Modular off-site construction factories are for the most part highly labour intensive and seldom make use of much automation. The size of the modules makes them particularly unwieldy and is problematic given the lack of space. Production at the factory is often not as efficient as it could be because companies produce modules according to the fixed module on-site installation sequence, which is subject to four installation constraints. The buffers between the factory and the construction site serve three main purposes: to re-sequence the production, should need be, before delivering the modules to the site and to shield against upstream and downstream disruptions. It is important that the processes upstream of the site adhere to schedule so as not to incur costly delay penalties and extra costs for operating the site for longer.

2.4 Review of operational disruptions and disruption management strategies

This section begins with a review of operational disruptions faced by modular off-site construction companies. To counter such disruptions, the concept of supply chain robustness is introduced as well as how it may be achieved. Key to this are disruption management strategies, for which a review of existing literature is provided. Finally, the importance of evaluating and selecting the appropriate disruption management strategies is explained along with a review of existing approaches. It should be noted that more detailed literature reviews of research methods are deferred to later chapters.

2.4.1 Operational disruptions in modular off-site construction systems

There has been limited research specifically dedicated to identifying operational disruptions in modular off-site construction. (Johnsson and Meiling, 2009) investigated defects (i.e. damage) in timber module production and transportation. They also reported damage as a result of lifting and depositing modules. (Shahtaheri *et al.*, 2017) investigated risks of production errors, transportation damage, and building installation drift as a result of misaligning modules during installation. (Hsu, Angeloudis and Aurisicchio, 2018) proposed a production planning model where disruptions at a bathroom pod manufacturer owing to bad weather conditions at the site, transportation issues, worker inefficiency, and crane unreliability and breakdown were reported. Similarly, (Hsu, Aurisicchio and Angeloudis, 2019) extended this model to incorporate risk aversion and investigated modular systems facing the same disruptions. (Godbole *et al.*, 2018) noted that damage to modules could occur during transportation when modelling the dynamic loads that they are subjected to. Research dedicated to identifying disruptions in non-modular off-site construction systems is more plentiful and the reader is referred to the following articles (Hassim, Sazalli and Jaafar, 2008; Luo *et al.*, 2015, 2018; Li *et al.*, 2016; Wu *et al.*, 2019).

It is evident from the above that modular off-site construction companies are subject to a range of disruptions. As such, these companies need to find ways to make their systems robust to these disruptions, as is explored next.

2.4.2 Robustness of supply chains to disruptions

There are several key supply chain concepts that have been explored in literature: robustness, responsiveness, and resilience. There is no consensus on their definitions: they have been given overlapping definitions and have been used interchangeably. For the purposes of this research, the following definitions and other concepts in this section were adopted from (Klibi, Martel and Guitouni, 2010):

- ***Robustness***: is the quality of a supply chain network to remain effective for all plausible futures.
- ***Resilience***: is the capability of a supply chain network to avoid disruptions or quickly recover from failures.
- ***Responsiveness***: is the capability of a supply chain network to respond positively to variations in business conditions.

Robustness can be viewed as a measure that companies seek to increase by ensuring that the system is resilient. The resilience of a system may be increased by transferring risk, avoiding risk, or by implementing responsive disruption management strategies[1]. Risk transfer includes strategies such as outsourcing, off-shoring, and contracting (Manuj and Mentzer, 2008). Risk avoidance includes strategies such as divestment, delaying entry to a new market, and participating in low uncertainty markets (Miller, 1992). Responsive disruption management strategies can be categorised as being either flexibility or redundancy-based. Flexibility-based strategies are “those which are developed by investing in SCN [supply chain network structures] and resources before they are needed”. Redundancy-based strategies make more resources available than are required to satisfy daily operations. As opposed to flexibility-based strategies, companies using redundancy-based strategies maintain excess capacity in case it may be needed to mitigate or avoid any loss in performance caused

[1] The term “capability” in (Klibi, Martel and Guitouni, 2010) has been used interchangeably with “disruption management strategy” (Urciuoli *et al.*, 2014) and is referred to as the latter herein.

by a disruption (Rice Jr and Caniato, 2003). The relationship between the concepts in this section has been summarised in Figure 2-5, where the enablers of a robust supply chain have been displayed in a hierarchical manner. Next, Section 2.4.3 gives a more detailed overview of literature on existing disruption management strategies.

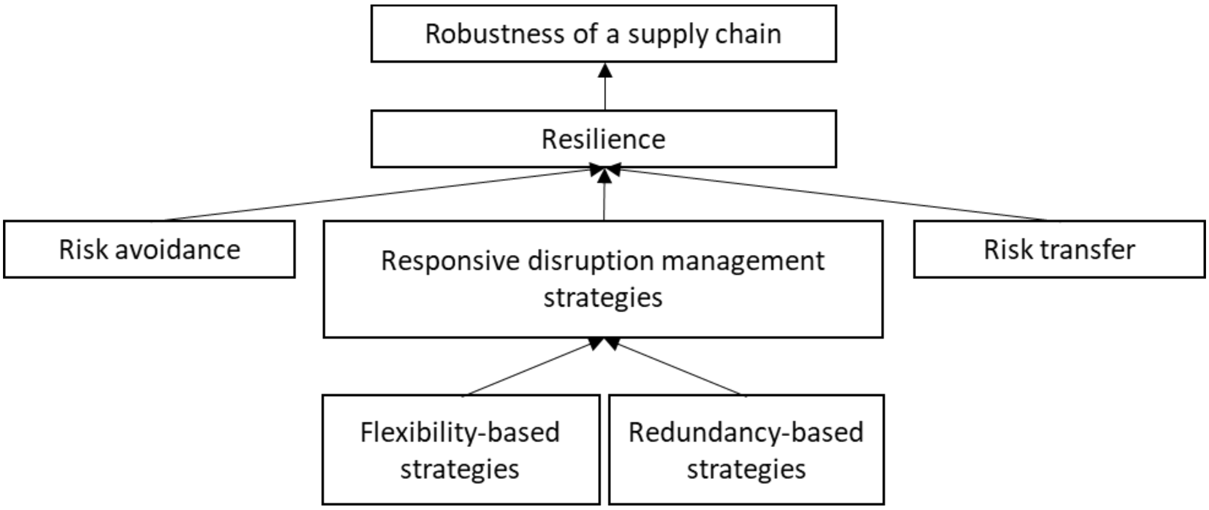

Figure 2-5: Illustration of the enablers to increase supply chain robustness.

2.4.3 Disruption management strategies in modular off-site construction

This section commences with an overview of the disruption management strategies reported in modular off-site construction literature. To complement this, a broader overview of the literature on disruption management strategies used in other industries is provided.

(Johnsson and Meiling, 2009) found that re-work and substitution were used by two Swedish modular off-site construction companies. (Arashpour *et al.*, 2015, 2018) investigated the use of multi-skilling as a disruption management strategy to counter labour shortages. (Hsu, Angeloudis and Aurisicchio, 2018; Hsu, Aurisicchio and Angeloudis, 2019) used the redundancy-based strategy of keeping safety stock in logistics planning. (Shahtaheri *et al.*, 2017) investigated how production errors, transportation damage, and building installation drift (as a result of misaligning a series of modules during installation) could be countered through re-work or over-engineering parts and processes (e.g. by imposing strict tolerances on the product and production system). Finally, (Goh and Goh, 2019) mentioned the use of re-work at the construction site to fix upstream disruptions.

Given the limited literature on modular off-site construction disruption management strategies, as shown above, an overview of strategies used in other industries is now provided. Recalling Section 2.4.2, disruption management strategies may be broadly categorised into two groups: flexibility-based and redundancy-based. Many different sub-categories of flexibility-based disruption management strategies have been identified in the literature. Indeed, (Manders, Caniëls and Ghijsen, 2017) identified 95 separate sub-categories. Citing all the types including all disruption management strategies that belong to them would go beyond what is needed for the purposes of this thesis. For a comprehensive breakdown, the reader is referred to the reviews by (Stevenson and Spring, 2007; Mishra, Pundir and Ganapathy, 2014; Jafari, 2015; Esmaeilikia *et al.*, 2016; Manders, Caniëls and Ghijsen, 2017)[2]. Instead, the following section highlights a selection of the most relevant flexibility-based disruption management strategies:

- **Volume flexibility strategies**: grant the ability to increase processing capacity temporarily (Tomlin, 2006). Some examples include *overtime* (Yang and Geunes, 2008), *options contracts* with suppliers which allow companies to increase the rate of deliveries (Barnes-Schuster, Bassok and Anupindi, 2003), and *temporary labour hire* (Kesavan, Staats and Gilland, 2014).
- **Operations flexibility strategies**: enable the completion of activities using alternative process plans, processes, and assets (Manders, Caniëls and Ghijsen, 2017). For example, implementing a *re-work* strategy whereby products are taken to an off-line process to be completed or corrected instead of holding up the main production line in the event of a disruption (Ding and Sun, 2007). Employing a *substitution strategy* allows companies, for instance, to re-assign a component destined for another product to one that requires it more pressingly as a result of a disruption (Bansal and Moritz, 2015).
- **Process flexibility strategies**: allow to produce different types of products (Hopp, Iravani and Xu, 2010). For example, (Graves and Tomlin, 2003) investigated a *production shifting strategy* whereby certain factories could be enabled to produce a large mix of parts to counter demand disruptions. A *multi-skilled workforce* strategy would enhance the system's ability to handle

[2] It should be noted when referring to the literature cited in this thesis that the definitions of flexibility-based and redundancy-based strategies have also been defined inconsistently and used interchangeably on occasions (Tiwari, Tiwari and Samuel, 2015). For instance, (Esmaeilikia *et al.*, 2016) state that having safety-stock is a "storage flexibility" whereas (Klibi, Martel and Guitouni, 2010) state that it is a redundancy-based strategy. Nevertheless, the classification defined in Section 2.4.2 will be adhered to when citing examples of each.

different products, for example, to counter disruptive shifts in market demand (Sethi and Sethi, 1990).

- **Procurement flexibility strategies**: give the ability to meet changing requirements regarding the sourcing, supply, or purchasing of materials (Manders, Caniëls and Ghijsen, 2017). For example, a system enabled by an *emergency shipment strategy*, to expedite the supply of parts (Alfredsson and Verrijdt, 1999; Özkan, van Houtum and Serin, 2013).
- **Logistics flexibility strategies**: whereby inbound and outbound activities, and the storage of parts and products are adjusted to suit changing customer requirements (Manders, Caniëls and Ghijsen, 2017). For example, an *interventionist order picking strategy* allows warehouse labour pick-lists to be updated mid-route with last minute orders (Giannikas *et al.*, 2017).
- **Sourcing flexibility strategies**: whereby there are multiple suppliers for a given component (Manders, Caniëls and Ghijsen, 2017). For example, a *multi-region supply chain strategy* can be used to hedge against foreign exchange disruptions (Minner, 2003).
- **Sequencing flexibility strategies**: allow a system to reorganise the order in which parts are processed (Schmenner and Tatikonda, 2005). One example of a disruption management strategy that belongs to this category is *re-scheduling*. This "is the process of updating an existing production schedule in response to disruptions or changes" (Vieira, Herrmann and Lin, 2003).

Regarding redundancy-based techniques, these include having insurance capacity (maintaining resources in addition to those needed to meet daily requirements of the system) (Klibi, Martel and Guitouni, 2010), safety stock (Tang, 2006), or adopting tighter tolerances to allow for distortions (Shahtaheri *et al.*, 2017). For a more detailed list of disruption management strategies, the reader is referred to (Tang, 2006; Kamalahmadi and Parast, 2016).

Despite the wide range of different disruption management strategies, it is important to note that not all may be applicable for a given industry. Indeed, (Carvalho and Junior, 2015) reported that each industry requires its own tailored way to approach risks. For instance, it is known that in the construction industry there is a shortage of skilled labour (Pan, Gibb and Dainty, 2007) and hence it may be difficult for companies to adopt an *overtime strategy* or *a temporary worker strategy*. Furthermore, certain modular off-site companies (such as those visited and reported on in Chapter 3) may source some of their key components from as far away as China to go to the UK. As such, implementing strategies such as *emergency shipments* may also not be feasible.

To summarise, very little research in modular off-site construction disruption management strategies has been carried out. Furthermore, disruption management strategies for other industries are not necessarily applicable to the modular off-site construction industry in view of its particular characteristics. The next section sets out how to evaluate and select between viable alternative strategies to achieve a robust system.

2.4.4 Methods to evaluate and select disruption management strategies

When choosing amongst different disruption management strategies, practitioners must weigh their benefits against their costs (Urciuoli *et al.*, 2014). Such decisions are often complex for several reasons. To begin with, it has been shown that investing too heavily in a single strategy may outweigh the benefits (Kesavan, Staats and Gilland, 2014). Furthermore, certain combinations of different disruption management strategies may not always be beneficial (Goyal and Netessine, 2011). Thus, it is important to develop methods, tools, and approaches to aid practitioners in their decision making.

To facilitate such decisions, there is a large body of research dedicated to evaluating the performance of such strategies as well as developing decision models to help select the optimal combination under uncertainty and constraints. The reader is referred to (Heckmann, Comes and Nickel, 2015; Ho *et al.*, 2015; Jafari, 2015; Snyder *et al.*, 2016) for in-depth reviews of the methods. However only limited research to help make such decisions specifically for modular off-site construction has been performed (Shahtaheri *et al.*, 2017; Hsu, Angeloudis and Aurisicchio, 2018; Hsu, Aurisicchio and Angeloudis, 2019). This is corroborated by (Li *et al.*, 2016), who suggested that because of "a lack of [an] effective framework for the analysis of cost/benefit… [of] risk mitigation actions, future research regarding… the development of [an] analytical framework for simulating the effectiveness of risk mitigation actions should be conducted, such that optimized risks mitigation action (*sic*) can be identified under different resource constraints". Hence, further research is needed to develop approaches to determine the appropriate choice of disruption management strategies for the modular off-site construction industry.

2.5 Research gaps, research aim, and research questions

2.5.1 Research gaps and research aim

Based on the section above, two gaps in the research on modular off-site construction disruption management were identified:

Research Gap 1: **There has been little research on identifying operational disruptions faced by modular off-site construction companies and disruption management strategies used to mitigate them.** (Hosseini *et al.*, 2018) concluded in their review of off-site construction literature that "operational and management themes are noticeably neglected." In a review of barriers to the adoption of modular off-site construction, (Hwang, Shan and Looi, 2018) concluded that "for future research, it is required to… examine critical risks… when… [modular off-site construction[3]]… is adopted". A general review of risks in all kinds of off-site construction observed that "no mitigation strategies were identified for the CRFs [Critical Risk Factors, including disruptions] and thus, future studies may investigate management strategies and their effectiveness in addressing the CRFs" (Wuni, Shen and Mahmud, 2019). Furthermore, "in-depth integration of risk management processes, from risk management planning to risk monitoring and controlling for modular construction, should be considered in future research" (Li *et al.*, 2013). What is more, no literature was found specifically mapping disruption management strategies to the disruptions that they counter in the modular off-site construction industry.

Research Gap 2: **There is a lack of disruption management strategies tailored to the specific needs of the modular off-site construction industry as well as tools to select and assess them**. The review in Section 2.4.3 of modular off-site construction disruption management strategies found that these were often adopted from traditional construction and other industries. However, (Carvalho and Junior, 2015) recommended that each industry should look to develop and enable tailored strategies to manage their particular risks. The review in Section 2.4.4 found that few tools have been developed specifically to evaluate the costs and benefits of

[3] Modular off-site construction is referred to as PPVC (prefabricated prefinished volumetric construction) in the article

modular off-site construction disruption management strategies. This observation was also corroborated by (Li *et al.*, 2016).

Research aim: To investigate operational disruptions in modular off-site construction and identify, propose, and assess disruption management strategies to mitigate them.

2.5.2 Research questions

In view of the above research aim and gaps, four research questions were devised.

Research Question 1 (RQ1): What are the main operational disruptions faced by the modular off-site construction industry and how do companies currently cope with such disruptions?

Research Question 1 addresses Research Gap 1 as it deals with identifying the main operational disruptions and the corresponding disruption management strategies for modular off-site construction. It aims to provide insight into how companies mitigate operational disruptions. In doing so, shortcomings of current strategies were uncovered.

To help overcome these shortcomings, a novel disruption management strategy tailored to the modular off-site construction industry of *on-site installation flexibility* was proposed. To assess on-site installation flexibility as a potential disruption management strategy, a further three research questions were posed:

Research Question 2 (RQ2): How can on-site installation flexibility be enabled?

Research Question 3 (RQ3): How can the appropriate level of on-site installation flexibility be selected to support effective disruption management?

Research Question 4 (RQ4): How does on-site installation flexibility affect the behaviour of modular off-site construction systems?

The proposal of on-site installation flexibility and Research Questions 2, 3, and 4 collectively address Research Gap 2.

Research Question 2 focuses on the more practical aspects of implementing on-site installation flexibility as a disruption management strategy. It aims to identify what steps and/or organisational changes are required to enable it. In addition, it aims to understand the order in which such steps should be implemented.

Research Question 3 deals with the decision faced by practitioners as to what disruption management strategies to implement. It aims to provide decision makers with an approach to selecting and evaluating the most appropriate level of on-site installation flexibility when other disruption management options are also available.

Research Question 4 deals with understanding how on-site installation flexibility affects the behaviour of modular off-site constructions systems. It aims to provide a quantitative evaluation of on-site installation flexibility measured against behaviour metrics important to practitioners.

2.6 Summary

This chapter aimed to: i) provide background information about modular off-site construction and supply chain robustness concepts and ii) position this work in the existing body of research as well as justify the research gaps, research aim, and research questions that this thesis addresses.

A review of the state of the art of off-site construction was conducted. In it the numerous benefits of using off-site construction as well as its drawbacks were explained. The main characteristics of modular off-site construction systems were then detailed. An overview of the main kinds of disruptions and supply chain robustness concepts was provided. To position the research in this thesis in the academic body of knowledge, a review was conducted of research on operational disruptions and disruption management strategies in the modular off-site construction industry. Furthermore, the importance of evaluating and selecting appropriate disruption management techniques for the modular off-site construction industry was highlighted. Based on the review, two research gaps were identified and four research questions were proposed to address them.

The first, RQ1, was concerned with identifying the operational disruptions and their disruption management strategies in the modular off-site construction industry. Building on the findings obtained when answering this question, shortcomings were identified in currently used strategies. A novel disruption management strategy of *on-site installation flexibility* was proposed to address these shortcomings. A further three research questions were then defined to assess: how a company can enable on-site installation flexibility (RQ2); how practitioners can decide on the appropriate level of on-site installation flexibility to support effective disruption management (RQ3); and how on-site installation flexibility affects the behaviour of modular off-site construction systems (RQ4). In proposing this novel strategy and answering these research questions, the research aim of investigating operational disruptions in modular off-site construction and identifying, proposing, and assessing disruption management strategies to mitigate them is addressed.

Chapter 3: Operational disruptions and disruption management strategies in modular off-site construction: an exploratory study

3.1 Introduction

The previous chapter highlighted the lack of research that has been done on operational disruptions and disruption management in the modular off-site construction industry. The focus of this chapter is on identifying the main operational disruptions faced by the modular off-site construction industry and how companies cope with them. The aims of this chapter are:

1. To provide insight into the main operational disruptions and disruption management strategies used by modular off-site construction companies.
2. To build an argument in support of the subsequent research into on-site installation flexibility as being of value not only from an academic perspective but also an industrial one.

A series of case studies and an industrial workshop were used to achieve these aims and answer the following four objectives:

1. Identify the key operational disruptions faced by modular off-site construction companies.
2. Identify the disruption management strategies currently used by modular off-site construction companies to deal with such disruptions.
3. Discuss the shortcomings of the current disruption management strategies.
4. Propose ways forward to address these shortcomings.

This chapter is structured as follows: Section 3.2 outlines the methodology used to address the above objectives. Section 3.3 gives an overview of the selected industrial participants in this study. The findings of the study are then reported in Section 3.4. Finally, the findings are discussed in Section 3.5.

3.2 Methodology

To identify the main operational disruptions and how companies deal with them, two methods of study were selected: case studies and a workshop (often referred to as a "focus group" in literature). This is known as *methodological triangulation* whereby a study is strengthened by using multiple methods to investigate the problem and combining the findings (Patton, 2015). Next, the justifications for choosing each method and their respective research designs are detailed.

3.2.1 Exploratory case study justification and research design

A case study based methodology is well suited to exploratory research, where the events being investigated are contemporary and their behaviour cannot be influenced (as opposed to experimental research) (Yin, 2014). Research Question 1, which is the focus of this chapter, was exploratory in nature given that there exists little relevant research, as highlighted in Chapter 2. Furthermore, this thesis investigated contemporary operational disruptions and management techniques. What is more, one could not control the phenomena being researched. A case study methodology is also well suited to address "How" research questions (Yin, 2014). The second part of the research question is itself a "How" question. Case studies were therefore a suitable method to be used.

The case study research design included several measures to ensure that the findings from the case studies were a reliable and an accurate representation of reality as well as generalisable beyond the immediate case studies. The quality of exploratory case study research is commonly judged according to three tests (Yin, 2014):

1. Construct validity test: Does the study procedure lead to an accurate representation of reality (Gibbert, Ruigrok and Wicki, 2008)?
2. External validity test: Can the findings from each participant in the study be generalised to others (Calder, Phillips and Tybout, 1982)?
3. Reliability test: Can the study be repeated and give the same results?

To ensure the construct validity, an extensive review was carried out in Section 2.4 where central concepts for disruption management were identified. These were explained when meeting representatives from the selected case studies to ensure everyone had the same understanding of the terms. What is more, a *data triangulation* approach was adopted, using a variety of sources of evidence to increase the confidence in the findings through corroboration (Patton, 2015) and further strengthen the construct validity (Gibbert, Ruigrok and Wicki, 2008). Three different sources of information were selected: interviews, direct observation (e.g. factory floor observations), and archival records (e.g. financial statements), as detailed in Appendix A.1.

To ensure external validity, a multi-case study approach was adopted for this research as it offers the possibility for direct replication of any findings (i.e. the ability to identify similar findings) (Yin, 2014). This is important as it helps to identify industry-wide operational disruptions and disruption management strategies rather than ones that are unique to individual companies. Furthermore, this study followed the recommendation from (Eisenhardt, 1989) that at least four case studies should be used. Several criteria (e.g. location, size, and target customer market) were formulated to select the participating companies to strengthen the external validity (Gibbert, Ruigrok and Wicki, 2008), as detailed in Appendix A.2. Additionally, (Gibbert, Ruigrok and Wicki, 2008) also recommended to provide context and background about the case study companies as in Section 3.3.

To ensure reliability of the case studies, several methods were used. Firstly, to give rigour to the case study research, it was important to follow a defined set of steps when planning and conducting case studies (Eisenhardt, 1989). Those used in this study are inspired from (Eisenhardt, 1989; Stuart *et al.*, 2002; Yin, 2014). The steps undertaken and their respective tasks are outlined in Table 3.1. Finally, a database was built up, primarily composed of field notes and post interview analysis, which further enhances the reliability of the findings (Gibbert, Ruigrok and Wicki, 2008).

Internal validity can be tested by comparing the findings through pattern matching with existing literature to strengthen confidence in the results (Gibbert, Ruigrok and Wicki, 2008). However, internal validity is not a test required for exploratory case studies such as this one (Yin, 2014). This is because the very nature of an exploratory study means that there is little literature against which the findings can be compared. Nevertheless, it was decided to compare the findings to existing non-modular off-site construction and traditional construction literature as a proxy to that of modular off-site construction literature as a degree of overlap was to be expected.

Table 3.1: Case study procedure.

Step	Tasks	Sub-tasks
Scoping	Define the research questions	Read relevant literature
	Define the aims of the study	
Preparation of case study approach	Select case study companies	Determine criteria to select the companies Short-list companies Contact companies
	Determine how data will be collected	Explain methods to be used to improve the data collection Select and justify primary sources of data Create visit checklist Write a list of semi-structured interview questions
	Determine how data will be analysed	
Data gathering	Visit the companies	
Data analysis	Complete within-case analysis	Identify main operational disruptions Identify disruption management strategies used to tackle them Identify any shortcomings in the disruption management strategies
	Complete cross-case analysis	Create a table showing which management strategy was used by which company to counter a given disruption
Dissemination of findings	Provide an overview of the case study methodology	
	Describe the individual case studies	Outline the context of the operations Highlight the main operational disruptions faced Describe the disruption management strategies used
	Report the main operational disruptions described by the companies	Describe any trends that may be observed across the cases
	Report the main disruption management strategies described by the companies	Describe any trends that may be observed across the cases Describe the shortcomings of the existing strategies Identify operational disruptions that would benefit from additional or alternative disruption management strategies

3.2.2 Exploratory workshop justification and research design

A workshop was chosen as an additional method of study as it works well in combination with case study interviews (Given, 2009) by providing a greater breadth of information (Crabtree *et al.*, 2019). Workshops allow researchers to obtain the answers to not only “What” questions but also “How” (Kitzinger, 1995) – both of which are a part of Research Question 1. Additionally, workshops have been used in the past for off-site construction research (Blismas, 2007; Goulding *et al.*, 2015) and hence are a recognised way of studying such systems. The purpose of the workshop was to complement and strengthen the findings from the exploratory case studies.

The design of the workshop was adapted from the steps outlined in (Knodel, 1993; Nyumba *et al.*, 2018) and can be seen in Table 3.2[4]. There are three key steps in the procedure: preparation, data collection, and data analysis. Each step is outlined in turn next:

1. **Preparation step**: The purpose of the workshop was to complement and strengthen the findings from the exploratory case studies. The workshop took a semi-structured approach with three guiding questions applied in turn to operations management, disruption management, and supply chain management:
    a. What are the challenges in this area?
    b. Why are they challenges?
    c. How are they currently being tackled (if at all)?

    The chosen questions were open ended as this helped to stimulate useful trains of thought that may not have been anticipated (Knodel, 1993). The study brought together a range of participants who worked in different areas of responsibility of modular off-site construction projects. Exploratory workshops such as this one are said to benefit from including participants from a broad range of perspectives (Kitzinger, 1995). The participant selection criteria are reported in Appendix A.2.

2. **The data collection step**: This lasted two hours. During the first five minutes of the workshop, participants were asked to introduce themselves to the group. This was followed by a brief overview of the study as well as the agenda for the day. Subsequently, participants were then given some time to consider each area and answer the three questions. Inspired from the procedure used in (Goulding *et al.*, 2015), participants were then split into three groups of five where they discussed their answers for a total of forty minutes. Each group was provided with a discussion moderator to guide the groups and ensure all participants had the opportunity to share their thoughts. Furthermore, they were provided with a flipchart to note the points made. The answers of each group were then shared and discussed with all participants collectively to extract further insights and contributions in a final forty-five minute plenary

[4] The workshop was run as part of a larger workshop organised for off-site construction. Some of the tasks, such as selecting the workshop participants and identifying a suitable location, was done in collaboration with other academics who were part of the AMSCI consortium and who were also present to facilitate the workshop.

session. In all, three sources of data were collected: individual notes made by the practitioners on the topics, the notes on the flip chart, and the notes made during the plenary session. This data was also complemented by notes from discussions with the participants during the breaks.

3. **Data analysis step**: The different notes were then gathered and transcribed into electronic form. Particular attention was paid to identifying operational disruptions and their respective disruption management strategies. Any mentions of the limitations of the disruption management strategies were also noted.

Table 3.2: Workshop procedure.

Step	Tasks	Sub-tasks
Preparation	Define the objectives of the study	Define the purpose of the workshop Create guiding questions
	Select workshop participants	Determine criteria to select the participants Short-list participants Contact participants
	Identify suitable location	Determine criteria to select a location Select a location
	Create background information for the participants	
	Ensure material supports are available and functioning	
Data collection	Facilitation	Participant introduction Overview of research presentation Ensure participants understand what is required Moderate the discussion Timekeeping
Data analysis	Identify main operational disruptions	
	Identify disruption management strategies	
	Record any shortcomings of disruption management strategies	

3.3 Overview of the selected participants

3.3.1 Exploratory case study participants

After conducting an online search for off-site construction companies and contacting those that matched the criteria, five companies summarised in Table 3.3 agreed to take part in the study.

Table 3.3: Case study company overview.

Company	Turnover 2016 (£m)	Avg. number of employees (2016)	Module structure material	Tallest building built (storeys)	Can act as main project contractor
Company A	25.6	249	Steel & concrete	17	Yes
Company B	20.1	180	Steel & concrete	23	No
Company C	45.3	162	Steel & concrete	29	No
Company D	300.2	1742	Steel & concrete	6	No
Company E	23.7	206	Timber	1	No

Company A: is a British company that provides off-site modular systems and pods to a range of customers, the primary ones being the defence, education, and hospitality sectors. Company A offers the possibility of producing modules in shapes that are not necessarily rectilinear and that are 70-80% finished by the time they leave the factory. They have the proven capability to construct buildings that have as many as 17 storeys. They currently have two production facilities, one arranged in a single production line style where modules progress from process to process, and another where modules are assembled in static positions in a large warehouse. In both cases, it is possible for modules to overtake one another should need be. Both facilities have the capacity to produce 2160 modules per year. Modules take between 20 and 25 days to produce depending on the level of complexity and they have anywhere between 300 and 400 modules in progress at any given time.

Company B: is a British company that builds volumetric off-site systems such as modules and bathroom pods. It has the capacity to produce 2100 modules or 7500 pods per year and employs a workforce of 180. Company B primarily provides modular buildings for hotels and the education sector, temporary housing solutions to the defence industry and private rented sector, and bathroom pods for the residential and health care sectors. The modular buildings that they offer have in the past reached up to 23 storeys high. Like Company A, the company prides itself on its capability to produce modules not only of rectilinear shape but also any shape that their client desires. It also has the capability to fit out the modules with Mechanical, Electrical, and Plumbing (MEP) systems and interior finishes prior to shipping. Their production is very labour intensive with little automation other than the rolling processes used to form the steel frame members. Modules and pods flow down an S shaped production line typically one multi-module project after another to achieve processing time reduction through the repetitive nature of the work.

Company C: is a British company that provides off-site modular systems to customers primarily from the hospitality, student accommodation, and residential sectors. Their systems are capable of being built up to 40 storeys high. Their production facility is located in the UK and has the capacity to produce 40 concrete-floored modules per week. The wall frames are imported in a pre-assembled state from overseas. The modules take approximately 2.5 weeks to produce on what is essentially a flow shop production line. The fit out is typically completed within the factory but the external cladding is done at the construction site mainly for aesthetic reasons. The company does not act as the main contractor on projects.

Company D: is a UK company that generates 60-70% of its turnover from its temporary building hire operation and 30-40% from its permanent building solutions. Its prime target market is the education sector, followed by the health, retail, and general commercial office sectors. All its buildings are constructed from modules that are manufactured in its production facilities in either the UK, France, or Germany. At any one time they have 30,000 modules in their hiring operation. The company itself manufactures many of the standardised components that are used throughout their module range (e.g. joints, brackets, etc.) and the vast majority of the structural elements for the modules except for the beams which are made to measure by an overseas supplier. The company's UK production facility is arranged as a job shop for initial operations, after which products are assembled on one of three flow shop production lines to make the frames of the modules. The flow lines use a high degree of automation for instance to lift large panels using a suction-operated mechanical handling system mounted on a gantry, laser CNC machines to cut doorways from wall panels up to 18m long, and a large special-purpose machine to produce insulated wall panels. The fit out of the modules is completed in a large outdoor yard, where some of the work is outsourced to external companies to, for example, fit the window frames into the modules.

Company E: is a British company that produces single storey houses which may be made of up to four modules. Its timber modular buildings cater to the hospitality, residential, and private rented sectors. The company produces modules in three factories across four production lines that produce approximately 15 homes per day. Little automation is used other than for primary material processing. The company produces 22 building models which can have up to 180 interior layout configurations. Furthermore, Company E also offers 205 “off the shelf” customisable options such as the location of electrical sockets. The modules are approximately 80% finished when they exit the factory.

The representatives of each company and the sources of information used for each company are listed in Table 3.4.

Table 3.4: Overview of interviews and other sources of information.

Company	Interviewees	Total duration	Other sources
Company A	Managing Director Head of Marketing	2h	Direct observation (1h30 factory tour) Archival records Documentation
Company B	Managing Director Head of Design	2h	Direct observation (1h30 factory tour) Archival records Documentation
Company C	Managing Director Head of Operations	2h	Direct observation (1h30 factory tour) Archival records Documentation
Company D	Business Manager Design engineer	1h30	Direct observation (1h30 factory tour) Archival records Documentation
Company E	Production Planner Production Manager Operations Director Operations Support Manager Systems architect	5h	Direct observation (2h factory tour) Archival records Documentation

3.3.2 Workshop participants

The participants in Table 3.5 agreed to take part in the industrial workshop.

Table 3.5: Workshop participants. Ind. = participant works in industry; Ac. = participant works in academia. * = workshop facilitator.

#	Type	Position	Company
1	Ind.	Director	Company B
2	Ind.	Design Management Leader	Company D
3	Ind.	Partner, Head of Production Information	UK Construction Consultancy A
4	Ind.	Founding Director	UK Construction Consultancy B
5	Ind.	Technical Director – Services	UK Construction Consultancy C
6	Ind.	Technical Director	UK Construction Consultancy C
7	Ind.	Business Development	UK Construction Consultancy D
8	Ind.	Director of Innovation & Business Improvement	Multinational construction and development company
9	Ind.	Product Development Leader	Multinational construction and development company
10	Ac.	Chief Engineer – Construction & Infrastructure, Strategic Development	Research and Technology Organisation A
11	Ac.	Head of Construction & Infrastructure Strategy	University A
12	Ac.*	Professor Industrial Information Engineering	University B
13	Ac.	Professor Infrastructure & Construction	University B
14	Ac.*	Professor in Design Engineering	University B
15	Ac.*	Senior Research Associate in Design & Manufacturing	University B
16	Ac.*	Research Associate in Manufacturing	University B
17	Ac.*	PhD Student in Manufacturing	University B
18	Ac.	PhD Student in Design	University B

3.4 Findings

The findings from the case studies and the workshop are brought together in this section.

3.4.1 Operational disruptions and strategies to cope

Sixteen operational disruptions and nine disruption management strategies were identified: Table 3.6 shows the operational disruptions faced by companies and the respective disruption management strategies that they used to cope with them. Letters "A" to "E" correspond to the five companies listed in Table 3.4. If their representatives mentioned that a particular disruption management strategy was used to manage a given disruption, the letter assigned to their company is added to the cell which intersects the disruption and the disruption management strategy. Similarly, the disruptions and their corresponding disruption management strategies that were reported by practitioners during the industrial workshop are indicated by a red asterisk. For example, the "C,*" written in the cell at the intersection of "Storage of module pending installation" and "Crane breakdown" indicates that this strategy is used by Company C to counter the disruption. It also indicates that this was mentioned during the workshop as a strategy to counter this disruption. In a similar manner to (Li *et al.*, 2013), the sixteen disruptions in Table 3.6 were categorised into groups according to four main areas of modular off-site construction operations: inbound to the factory, in the factory itself, between the factory and the construction site, and at the construction site. For certain disruptions (e.g. labour shortages), some companies accepted them as a fact of life and did not have any strategy to address them. These have been indicated in the "Acceptance" column of Table 3.6. Full explanations of each disruption and disruption management strategy using examples uncovered during the study are provided in Appendix A.3 and Appendix A.4 respectively.

It was found that the companies did not all face the same set of disruptions. The disruptions most frequently reported by the case study companies were *materials not being delivered on time* to the factory, *component damage during production*, *high-wind conditions* at the site, and building *foundations not completed on time* – each being cited by four out of the five companies visited.

It was also found that companies may use different disruption management strategies to cope with the same disruptions. The companies had one or more disruption management strategies for at least three-quarters of the disruptions that they faced. However, no disruption management strategies were reported for four of the disruptions: *lack of skilled labour*, *difficulties in unloading modules*, *unforeseen obstacle preventing passage*, and *congestion during transport*. Finally, all companies used *re-work* and *storage of module pending installation*, the latter countering eleven of the sixteen disruptions – more than any other.

It is important to have effective strategies to cope with disruptions as they can cause significant costs and delays: Participants in the study reported that the disruptions often resulted in significant costs to modular off-site construction companies. This is because these disruptions frequently delayed the installation of modules at the construction site. They explained that a delay in a module's installation means that on-site labour and equipment must be hired for a longer period — often at a premium. Additionally, any post-installation work such as testing MEP systems on completed floors may be delayed, also at a cost. All these could lead to overall project delays and hence costly penalties for not completing the project on time.

On-site installation sequence constraints exacerbate delays caused by certain disruptions: Based on the discussion with the participants of the study, the disruptions were categorised into two types. A *Type 1* disruption (indicated with a "Y" in the last column of Table 3.6) is where the installation of a module is delayed because of it being damaged (e.g. during production or transport) or unfinished (e.g. material shortages). All subsequent modules in the on-site installation sequence must therefore be stored while the delayed module is completed because of the on-site installation constraints reported earlier in Section 2.3.4. Hence there is a knock-on effect on other completed modules. A *Type 2* disruption prevents modules from being installed regardless of any on-site installation constraints (e.g. high-wind conditions and congestion during transport).

Table 3.6: Operational disruptions and their management strategies as found in the study.

Location	Disruption	Disruption management strategies: Re-work module to remedy issue	Storage of module pending installation	Send module to site partially finished	Overtime to make up for lost time	Substitute component with similar part	Safety stock of parts	Vertical integration	Risk management built into contract	Produce more than one project at a time	Acceptance	Number of case companies affected	# management strategies	Type 1 disruption
Inbound to factory	Material not delivered on time	A,B,C,E,*	A,B,C,E,*	A,B,E	A,E,*	C	B,C,*		B,*	A		4	8	Y
Inbound to factory	Incorrect material delivered	A,B,E,*	A,B,E,*	A,B,E	A,E,*				B,*	A		3	6	Y
Factory	Component damage during production	A,D,E,*	A,D,E,*	A,E	A,E,*	A			B,*	A		4	7	Y
Factory	Design change request during production	B,E	B,E							A		3	3	Y
Factory	Lack of skilled labour										B,E	2	0	
Factory to site	Damage during storage	E,*										1	1	Y
Factory to site	Damage during transport		A,C,*						B,*	A		3	3	Y
Factory to site	Congestion during transport										B,*	1	0	
Factory to site	Unforeseen obstacle preventing passage										B,C,*	2	0	
Factory to site	Lack of haulage availability		B,C,E					B				3	2	
Factory to site	Lack of escort vehicle availability		B,C					B				2	2	
Factory to site	Difficulties in unloading modules										*	0	0	
Construction site	High-wind conditions		A,B,D,E,*							A		4	2	
Construction site	Foundations not completed on time		A,B,D,E,*							A		4	2	
Construction site	Lack of crane availability		B,C,*							A		3	2	
Construction site	Crane breakdown		C,*									1	1	
	Number of case companies using	5	5	3	2	2	2	1	1	1				
	Total number of times mentioned	17	38	8	9	2	3	2	8	8				
	Number of disruptions countered	5	11	3	3	2	1	2	4	8				

3.4.2 Shortcomings of the current disruption management strategies

This study revealed five main issues concerning disruption management in the modular off-site construction industry:

1. ***Current disruption management strategies do not always meet a company's needs to address its disruptions***: The reasons for this are twofold: i) the disruptions are beyond the control of the company and as such little can be done to manage them, or ii) the drawbacks of potential disruption management strategies outweigh their benefits. Examples of the first are *congestion during transport* and *unforeseen obstacle preventing passage*. Examples of disruption management strategies rejected for the second reason include:
    - *Cross-training labour*: If there is a *lack of skilled labour* (i.e. a specialised craftsman), a cross-trained resource can fill in. Company B stated that they were reluctant to use this strategy as in the past their investment in cross-training the workforce was often lost as the newly certified personnel left for better jobs or to work for themselves.
    - *Send module to site partially finished*: Company C opposed the use of such a strategy given the additional costs of hiring, transporting, and accommodating extra labour at the site to complete the work. Furthermore, in their opinion the loss in quality and efficiency that would otherwise have been offered at the factory is not justified.
    - *Produce more than one project at a time*: Company B stated that they only produce one project at a time so that the operators can familiarise themselves with the work and thereby reduce production time and errors.

2. ***Current disruption management strategies do not effectively mitigate all disruptions***: Even though several disruption management strategies were cited as countering a given disruption, the companies reported that some strategies could not be implemented at every occurrence or could not wholly mitigate the disruption. Hence, delays were reported to occur even though a strategy was employed. Examples mentioned during the study were:
    - *Re-work module to remedy issue*: Even though re-work allows modules to be completed off-line and hence production of follow-on modules to continue, the overall project will suffer a delay until the re-worked module is installed on site.
    - *Overtime to make up for lost time*: The drawback for companies that use such a strategy is that the labour cost per hour is higher. Furthermore, it is not always

possible to arrange at short notice given the skilled labour shortage as mentioned by company E.

- *Substitute component with similar part*: While this allows production to continue, it is typically only possible for components that have the same performance, and that are not visible to the end user. Company A however gave an example that they once replaced missing window units with another type of the same size.
- *Safety stock of parts*: Holding stock as work in progress ties up cash. Company B stated that stocking material to the desired level ahead of time was not always possible because of tight project deadlines or maintaining continuity of work on the production line.
- *Risk management built into contract:* Company B stated that even though sharing benefits and costs in their contracts is a good approach to managing risks, their client organisations are not always willing to adopt such an approach.

3. ***There is an over-reliance on storing modules as a disruption management strategy***: The above shortcomings, combined with there being few disruption management strategies for disruptions downstream of the factory, means that module storage is overly relied upon, as shown in Table 3.6. To complicate matters further, the use of storage exposes the system to further risks of disruption including damage during storage, damage during transport to and from the storage and when unloading and loading modules.

4. ***Storing modules will become a less viable disruption management strategy as the industry grows***: Currently this strategy is still feasible for many companies given that factory operations in modular off-site construction are not automated for the most part and are akin to having a construction site in a warehouse and hence have low production rates (Linner and Bock, 2012). However, this is not likely to remain the case for long as the industry grows.

   Already some of the participants of the study stated that storage space was a serious issue for them as they have had to resort to costly emergency storage space in the event of long-lasting disruptions during high volume projects. One of the participants during the workshop stated that within the next five years, their company is aiming to produce modules at a rate of one every ten minutes – six times faster than the companies that were visited in this study. Furthermore, it is envisaged that future projects will each comprise several hundred modules – again much larger than the projects currently run by the companies visited. In such a fastpaced environment, the use of storage space as a disruption management strategy will become problematic for several reasons.

Companies will have to invest in very large and costly storage areas to be able to accommodate all the modules being produced at a higher rate. In certain instances, companies have been forced to hold up the whole production line when there was nowhere to store modules, which is already costly and will be even more expensive in the future. In addition, stored modules are also susceptible to damage from exposure to the weather or vandalism – which will only get worse with increasing speed and size of projects. Should companies instead turn to emergency storage, it is likely to be difficult to find large areas near the site at short notice (if any), meaning increased risks of transport-related disruptions. Hence, in future the use of buffer storage as a disruption management strategy will only become more challenging to manage.

5. ***There are few disruption management strategies that prevent the knock-on installation delays caused by Type 1 disruptions***: Completed modules are prevented from being installed because of the on-site installation constraints when a Type 1 disruption occurs. Again, this is because the on-site module installation follows a fixed sequential order and therefore must be halted until the affected module is installed. Currently there is no way of avoiding this and the only answer is to provide additional storage space, the need for which will only grow in future.

In this section, the main operational disruptions were identified and disruption management strategies to counter them were mapped. In addition, shortcomings of the disruption management strategies were detailed. In the next section, the validity of these findings is discussed and ways of addressing these shortcomings are proposed.

3.5 Discussion of the findings

This section commences with an analysis of the validity of the findings. Ways forward to address the shortcomings of current disruption management strategies for modular off-site construction are then proposed.

3.5.1 Analysis of the validity of the findings

To give confidence in the findings, an analysis of their validity based on the tests outlined in section 3.2.1 was conducted. Both the external and internal validity were verified.

The external validity was tested by checking whether the following were corroborated by two or more case studies or the workshop and at least one case study: i) each identified disruption and disruption management strategy, and ii) the mappings between disruptions and the disruption management strategies. The results are discussed below:

- **A significant number of operational disruptions and disruption management strategies were corroborated**: Figure 3-1 shows that 94% of disruptions and 78% of disruption management strategies were corroborated. *Difficulties in unloading modules* was only mentioned in the workshop. 22% of the disruption management strategies were not corroborated because *Vertical integration* is only used by Company B and *Produce more than one project at a time* is only used by Company A. These appear to be more unconventional approaches to modular off-site construction operations.

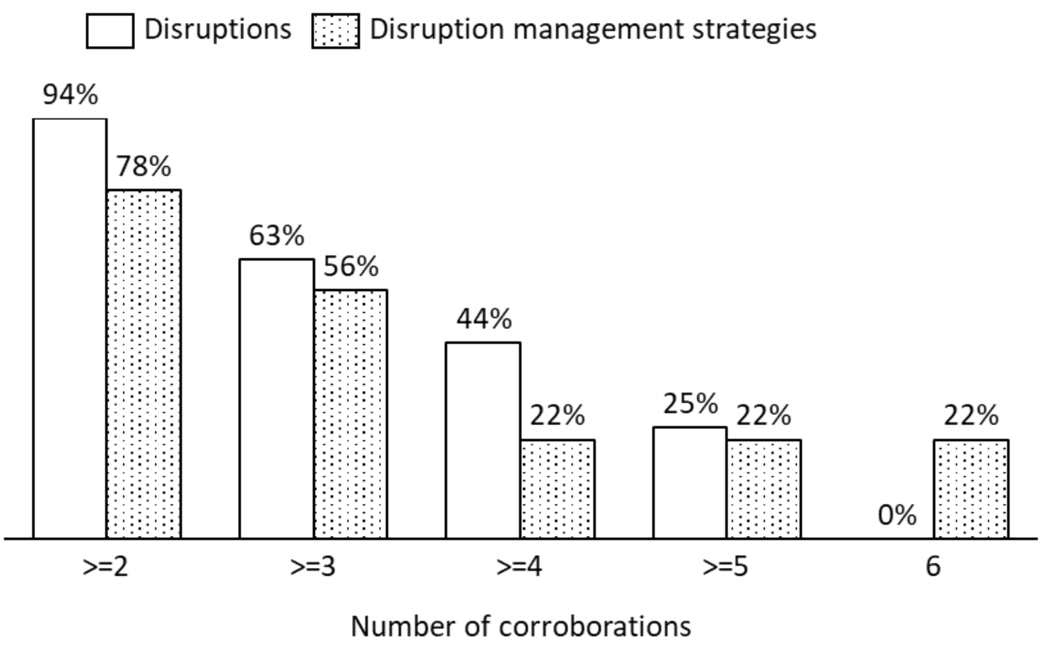

Figure 3-1: Percentage of the total number of disruptions and disruption management strategies which were corroborated to varying degrees.

- **A high degree of corroboration was found regarding the mappings of disruption management strategies to disruptions**: In Table 3.6, disruption management strategies that were reportedly used to counter a given disruption were mapped. Figure 3-2 shows the percentage of these mappings that were corroborated at least two, three, four and exactly five times. 70% of the mappings (i.e. 30 of them) were corroborated by at least twice, which gives confidence in the results.

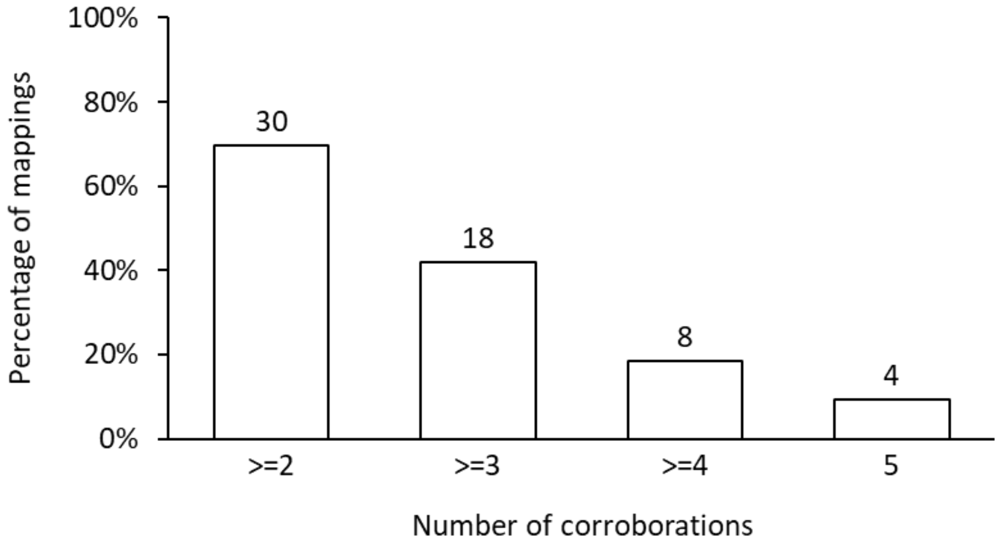

Figure 3-2: Percentage of mappings broken down by different degrees of corroboration.

There are several reasons why the remaining 30% of mappings were not corroborated by more than one source. Firstly, the study did not explicitly ask participants whether they used a particular disruption management strategy to counter a specific disruption. This was to avoid introducing any bias into the study by influencing the participants' responses and to concentrate on the main operational disruptions and their management strategies. Secondly, as stated earlier two of the disruption management strategies were used by one company each, and these alone accounted for over two thirds of the remaining uncorroborated mappings.

To verify the internal validity of the findings, pattern matching between the literature and the findings was used, as recommended by (Gibbert, Ruigrok and Wicki, 2008). Table 3.7 and Table 3.8 show the modular off-site construction articles identified in the review of Section 2.4 matched against those found in this study, for disruptions and disruption management strategies respectively. Literature on non-modular off-site and traditional construction was considered when no references were found dealing specifically with modular off-site construction, as a degree of overlap can be expected. Each table will now be discussed in turn:

- **56% of the identified disruptions have not previously been reported in modular off-site construction literature but many were found in the wider construction literature**: Table 3.7 shows that nine of the sixteen disruptions have not been identified previously in modular off-site construction literature. That said, 75% of them have been identified in general off-site construction (OSC) and construction literature, which gives confidence in the findings as overlaps are to be expected. However, 25% of them appear to be unique to the modular off-site industry: lack of haulage and escort vehicle and crane availability as well as difficulties in unloading the modules. One explanation for the first three is that as a result of the unique requirements of the large and heavy modules in terms of equipment as well as the marked increase in uptake of modular off-site construction, the contracting companies have not reacted to the increase in demand for their services. This could potentially be explained by wariness to invest in catering for a market that is only just beginning to gain significant traction.

Table 3.7: Alignment of disruptions found in this study with those reported in literature.

Location	Disruption	Literature: Modular OSC	Literature: General OSC & Construction
Inbound to factory	**Material not delivered on time**		(Li *et al.*, 2013)
Inbound to factory	**Incorrect material delivered**		(Kog, 2018b)
Factory	**Component damage during production**	(Johnsson and Meiling, 2009; Shahtaheri *et al.*, 2017)	(Wang, Hu and Gong, 2018)
Factory	**Design change request during production**		(Li *et al.*, 2013)
Factory	**Lack of skilled labour**	(Arashpour *et al.*, 2018)	(Zhai, Reed and Mills, 2014)
From factory to site	**Damage during storage**		(Wu *et al.*, 2019)
From factory to site	**Damage during transport**	(Johnsson and Meiling, 2009; Shahtaheri *et al.*, 2017; Godbole *et al.*, 2018)	(Lu and Yuan, 2013)
From factory to site	**Congestion during transport**	(Hsu, Angeloudis and Aurisicchio, 2018; Hsu, Aurisicchio and Angeloudis, 2019)	(Blismas, Pasquire and Gibb, 2006; Jaillon and Poon, 2009)
From factory to site	**Unforeseen obstacle preventing passage**		(Jaillon and Poon, 2009; Rahman, 2013)
From factory to site	**Lack of haulage availability**		
From factory to site	**Lack of escort vehicle availability**		
Construction site	**High-wind conditions**	(Hsu, Angeloudis and Aurisicchio, 2018; Hsu, Aurisicchio and Angeloudis, 2019)	(Li *et al.*, 2013)
Construction site	**Foundations not completed on time**		(El-Razek, M. E. Abd; Bassioni and Mobarak, 1995; Gündüz, Nielsen and Özdemir, 2013; Kog, 2018a)
Construction site	**Lack of crane availability**		
Construction site	**Crane breakdown**	(Hsu, Angeloudis and Aurisicchio, 2018; Hsu, Aurisicchio and Angeloudis, 2019)	(Li *et al.*, 2013)
Construction site	**Difficulties in unloading modules**	(Johnsson and Meiling, 2009)	

- **Over half of the identified disruption management strategies have not previously been reported in modular off-site construction literature but many were found in general disruption management literature**: Table 3.8 shows that five of the nine disruption management strategies found in this study have not been identified previously in modular off-site construction literature. However, all except one of them have been used in traditional and non-modular off-site construction. This shows that the modular off-site construction industry can benefit from imitating other industries for disruption management given that several have been carried over into modular off-site operations. Moreover, this overlap gives additional confidence in the validity of the findings.

Sending modules partially finished from the factory has not been reported previously and is particular to the modular off-site construction industry. The closest disruption management strategy found in literature is that of *postponement* which “is about delaying activities (as to the form and/or place of goods) until the latest possible point in time” (Yang, Burns and Backhouse, 2004). However, postponement decisions such as those described in the latter article are more long-term strategic ones (e.g. in which country or which stage in the process should products with common components be differentiated?). The strategy reported here is a flexible, short-term reaction to disruptions and not a permanent, one-time decision. This study has thus uncovered a novel form of postponement used as a disruption management strategy that has not been reported previously in disruption management literature.

Table 3.8: Alignment of disruption management strategies found in this study with those reported in literature.

Disruption management strategy	Literature: Modular OSC	Literature: General disruption management
Re-work module to remedy issue	(Johnsson and Meiling, 2009; Shahtaheri *et al.*, 2017; Goh and Goh, 2019)	(Alvanchi *et al.*, 2012; Kog, 2018a)
Store modules pending installation	(Hsu, Angeloudis and Aurisicchio, 2018; Hsu, Aurisicchio and Angeloudis, 2019)	(Ergen, Akinci and Sacks, 2007)
Send module to site partially finished		
Overtime to make up for lost time		(Szczesny and König, 2015)
Substitute component with similar part	(Johnsson and Meiling, 2009)	(Ferreira, Arantes and Kharlamov, 2014)
Safety stock of parts	(Hsu, Angeloudis and Aurisicchio, 2018; Hsu, Aurisicchio and Angeloudis, 2019)	(Vidalakis, Tookey and Sommerville, 2011)
Vertical integration		(Krippaehne, McCullouch and Vanegas, 1992)
Risk management built into contract		(Williams, 1996)
Produce more than one project at a time		(Aritua, Smith and Bower, 2009)

To summarise, the validity of the findings of this study have been assessed and can be treated with confidence:

- A significant number of operational disruptions and disruption management strategies were corroborated.
- A high degree of corroboration was found regarding the mappings of disruption management strategies to disruptions.
- 56% of the identified disruptions have not previously been reported in modular off-site construction literature but many were found in the wider construction literature.
- Over half of the identified disruption management strategies have not previously been reported in modular off-site construction literature but many were found in general disruption management literature.

The next section will look at ways to address the shortcomings of the identified disruption management strategies.

3.5.2 Ways forward

To tackle the shortcomings in current disruption management strategies that result in i) certain disruptions being difficult to mitigate effectively, and ii) the over-reliance on module storage which will become less effective as the industry grows, two ways forward are suggested:

1. ***Shift from a project-centric organisation to a product-centric organisation to reduce the effect of the drawbacks of certain existing disruption management strategies and alleviate the over-dependence on storing modules:*** One executive from the large multinational construction company stated that modular off-site construction companies need to shift from being project-centric organisations to being product-centric ones. This could be achieved by developing a product platform as in the automotive industry where multiple products share common components. As well as economies of scale, this could potentially address some of the drawbacks of certain disruption management strategies mentioned by the modular off-site construction companies. For example, it would increase the likelihood of substitute components being available. Furthermore, safety stocks would be easier to maintain if components are shared across multiple products. What is more, such an approach would encourage the companies to make their production processes more generic and streamlined. One method of doing this is to de-skill the production tasks, as has been done in traditional construction and the automotive industry (Haakestad and Friberg, 2017). This would reduce the need for skilled labour and make overtime more feasible to arrange at short notice. Finally, losses of efficiency and increased error rate on the factory floor that occur when producing more than one project at a time would be alleviated since more tasks would be generic across different products.

2. ***Develop alternative disruption management strategies specifically tailored to the modular off-site construction industry by exploiting its unique characteristics*:** For example, to counter the case of high wind disruptions at a site, a recently proposed disruption management strategy of *dynamic postponement* (Robertson, Srinivasan and McFarlane, 2019) could be used to send and install part-finished modules at site ahead of a forecast weather disruption

so that subsequent on-site work is not delayed by the inoperability of the crane. This strategy exploits the fact that modules do not have to be fully completed before leaving the factory – something unique to modular off-site construction. However, it comes at the cost of completing the modules less efficiently at the site and at a likely premium as additional on-site labour is required.

A more specific way forward that reduces not only the over-reliance on module storage but also the knock-on delays caused by Type 1 disruptions on modules that are otherwise ready to be installed is as follows:

3. ***Develop a disruption management strategy that relaxes the on-site installation constraints to reduce knock-on installation delays caused by Type 1 disruptions***: One potential way to address the knock-on effect caused by Type 1 disruptions on modules that are otherwise ready to be installed, is to devise a disruption management strategy that would relax the on-site installation constraints. Not only can locations in the building then be filled with modules in a different order but also modules can be re-assigned to a different location in the building. In other words, should a module be disrupted, the installation of subsequent modules would not have to be delayed whilst it is being fixed. Instead the modules would proceed to be installed in a flexible order at the site rather than being temporarily stored. Figure 3-3 shows the module installation timeline for a building with 10 modules where a certain level of flexibility has been enabled. Three scenarios are shown: i) No disruptions, modules installed as planned within 10 time periods, ii) Module 6 is delayed for 4 time periods and because there is no flexibility, modules must be stored until Module 6 is delivered to the site. The project is completed in 14 time periods, iii) Module 6 is delayed for 4 time periods but flexibility allows installation of subsequent modules to continue as planned and the project is completed in 11 time periods. Hence, the project delay is reduced from four time periods to only one.

Time period	1	2	3	4	5	6	7	8	9	10	11	12	13	14
No disruption	1	2	3	4	5	6	7	8	9	10				
Disrupted without flexibility	1	2	3	4	5					6	7	8	9	10
Disrupted with flexibility	1	2	3	4	5		7	8	9	6	10			

= Module number

Figure 3-3: Module installation timeline showing the effect of flexibility when a module is disrupted.

Several additional benefits may be achieved by using this strategy such as time and cost savings by, for instance, not having to find and maintain larger storage spaces. Furthermore, the logistics of transporting modules from the factory to the storage area and from the storage area to the site would be reduced. Additionally, the likelihood of damaging the modules through repeated loading and unloading from vehicles would be significantly reduced. Drawbacks may include additional upfront investment in research and development to produce a building design capable of being assembled with flexibility. This novel disruption management strategy will hereafter be referred to as *on-site installation flexibility* and is the focus of the remainder of this thesis.

3.6 Summary

This chapter aimed to identify the main operational disruptions and disruption management strategies used by modular off-site construction companies. This was achieved by visiting and interviewing senior management and employees of five case study companies as well as organising an industrial workshop. The findings of this study were assessed for validity and can be treated with confidence.

In all, sixteen disruptions and nine disruption management strategies were identified, fulfilling objectives 1 and 2 of this chapter. In doing so, the disruption management strategies were mapped onto the disruptions to give an overview of how modular off-site construction companies cope. It is important to have effective disruption management strategies given that the disruptions can give rise to significant costs and delays. It was also found that on-site installation sequence constraints exacerbate knock-on module installation delays caused by Type 1 disruptions. Several shortcomings of the disruption management strategies were identified and discussed, answering objective 3:

1. Current disruption management strategies do not always meet a company's needs to address its disruptions.
2. Current disruption management strategies do not effectively mitigate all disruptions.
3. There is an over-reliance on storing modules as a disruption management strategy.
4. Storing modules will become a less viable disruption management strategy as the industry grows.
5. There are few disruption management strategies that prevent the knock-on installation delays caused by Type 1 disruptions.

To address these shortcomings and accomplish objective 4, three ways forward were proposed:

1. Shift from a project-centric organisation to a product-centric organisation to reduce the effect of the drawbacks of certain existing disruption management strategies and thereby alleviate the over-dependence on storing modules;
2. Develop alternative disruption management strategies, such as *dynamic postponement*, specifically tailored to the modular off-site construction industry by exploiting its unique characteristics*;*
3. Develop a disruption management strategy that relaxes on-site installation constraints to reduce knock-on installation delays caused by Type 1 disruptions, notably *on-site installation flexibility*.

The remainder of the research focuses on the third proposal and the following issues: i) how a company can enable on-site installation flexibility, ii) how practitioners can decide on the appropriate level of on-site installation flexibility to support effective disruption management, and iii) how on-site installation flexibility affects the behaviour of modular off-site construction systems.

Chapter 4:
Enabling on-site installation flexibility

4.1 Introduction

In the previous chapter, the idea of on-site installation flexibility was introduced as a novel strategy for managing disruptions in modular off-site construction systems. The focus of this chapter is on how on-site installation flexibility can be enabled. In this chapter, four different types of on-site installation flexibility are proposed and implementation roadmaps for each are devised. The objectives of the chapter are:

1. To define and validate the different types of on-site installation flexibility.
2. To identify the different enablers of each type of on-site installation flexibility.
3. To understand the interdependencies between the different enablers (e.g. does Enabler A have an influence on the enablement of Enabler B and vice-versa?).
4. To create implementation roadmaps that show the order in which the enablers should be implemented.

The motivation for creating on-site installation flexibility for disruption management is explained in Section 4.2. Next, four different types of on-site installation flexibility are proposed in Section 4.3. In Section 4.4, the practicalities of how to implement the different types of on-site installation flexibility are reported as well as their managerial implications, including implementation roadmaps and an analysis of the enablers required for each.

4.2 Motivation for creating on-site installation flexibility

In Chapter 3, several issues were pointed out that motivate the need for a novel disruption management strategy of on-site installation flexibility:

1. 38% of the main operational disruptions were identified as Type 1 disruptions which frequently cause knock-on module installation delays as a consequence of the four on-site installation constraints (defined in Section 2.3.4). These are shown in Figure 4-1.
2. Current disruption management strategies do not effectively mitigate Type 1 disruptions, resulting in an over-reliance on storing modules as a disruption management strategy and acceptance of the associated delay.
3. In future, more modules are likely to need to be stored, given: i) the increasing production rates as technological advances are made, ii) the reduction of slack in the system because of lean manufacturing practices, and iii) increasing project sizes, as reported previously in Section 1.1. Given the size of the modules and the limited space available, storing modules will therefore become a less viable disruption management strategy.

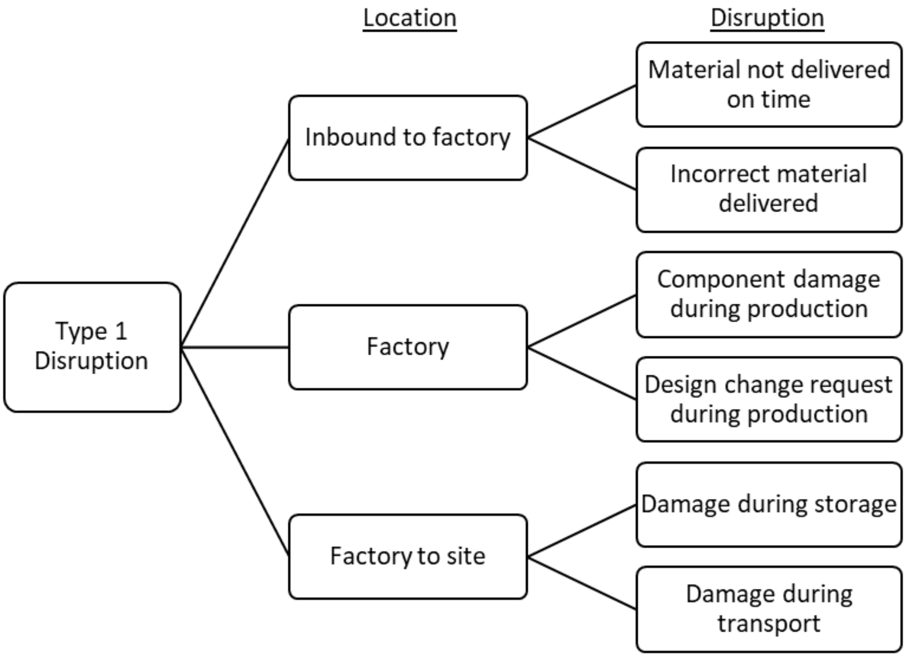

Figure 4-1: Type 1 disruptions identified in Chapter 3.

It would therefore be of benefit and importance to create a way to relax the four on-site installation constraints for more effective disruption management now and, more critically, in the future to avoid significant project delays and costs.

4.3 Types of on-site installation flexibility

4.3.1 Overview

In this section four types of on-site installation flexibility are newly proposed and introduced. Flexibility of on-site installation can be achieved by relaxing the on-site installation constraints such that:

i. The *slot* (i.e. location in the building) in which a module is installed can be flexibly chosen, herein referred to as *slot assignment flexibility*.
ii. The *sequence* in which slots have modules installed into them is flexible, herein referred to as *slot installation sequence flexibility*.

Each has a “vertical” and a “lateral” variant that specifically target one of the four on-site installation constraints. Figure 4-2 shows the four newly proposed on-site installation flexibilities and the on-site installation constraints that they relax. These flexibilities are explained further in this section with a focus on their disruption management benefits.

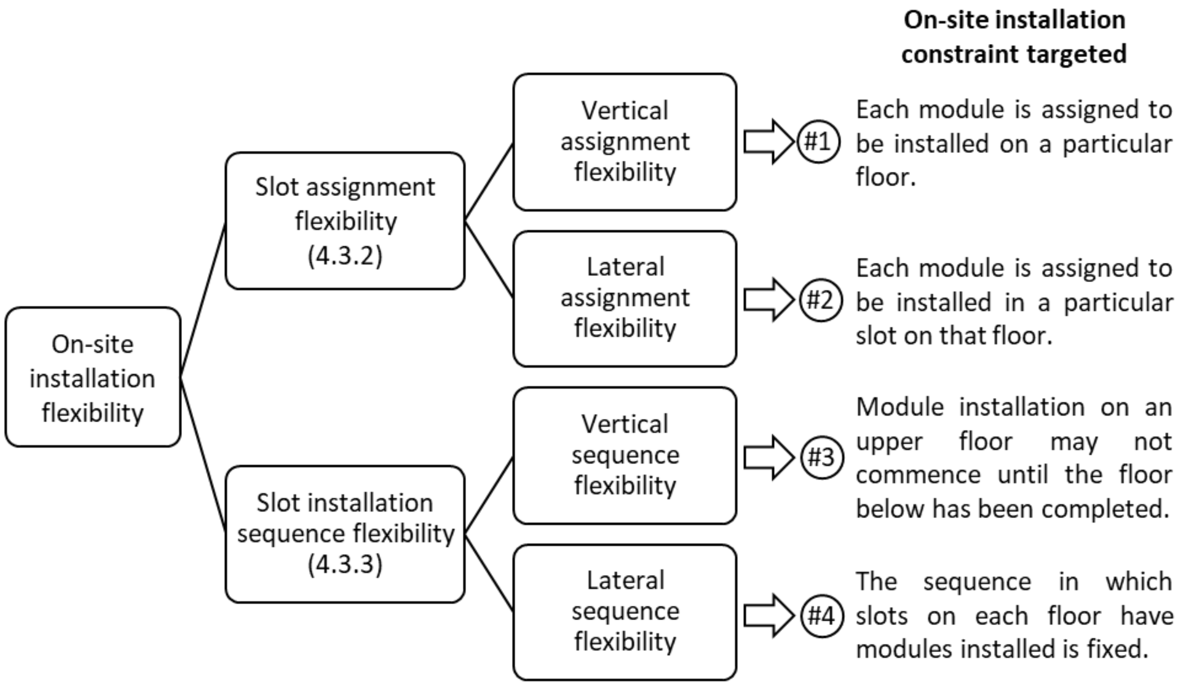

Figure 4-2: Different types of on-site installation flexibility and the on-site installation constraints that they relax. The section numbers in which they are further explained are shown in brackets.

4.3.2 Slot assignment flexibility

Slot assignment flexibility is concerned with the assignment of modules to slots. The concepts of *finish similarity*, *structural similarity*, and *module type* are now introduced. These help to determine whether a module can be re-assigned to another slot in the building using slot assignment flexibility. Only modules of the *same* module type can be re-assigned.

Definition 5: Finish similarity
Two modules are said to have finish similarity when they are identical in terms of finish (both interior & exterior) even if their structural elements are not the same. For example, two modules with finish similarity may still have structural columns of different strengths, depending on the storey in a building for which they are intended.

Definition 6: Structural similarity
Two modules are said to have structural similarity when they can each bear the load that either would be subjected to if their slot assignments were to be interchanged. All modules on a given floor are structurally similar.

Definition 7: Module type
Two modules are said to be of the same type if they both have the same finish and structural similarity when they arrive at the construction site to be installed.

To best illustrate the benefits of the different types of on-site installation flexibility for disruption management purposes, a simple hypothetical yet realistic scenario is now developed. Consider the floor plan of the narrow two-storey building depicted in Figure 4-3. Each floor ends with two cores, the main locating structures to which modules are fastened. Each floor has five slots in which modules may be installed. When no disruptions occur, the installation process follows the nominal slot installation sequence which fills the slots numbered from lowest to highest. This scenario is referred to as the *base scenario* and is subject to minor alterations to bring out the benefits of each on-site installation flexibility type below.

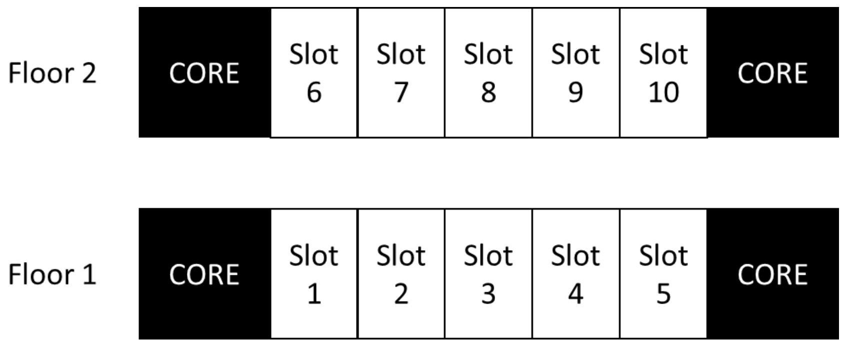

Figure 4-3: Floor plan for example disruption scenario.

Definition 8: Vertical assignment flexibility

Is the ability to install a module on a floor other than the one for which it was originally intended.

If the module assigned to Slot 5 is disrupted, enabling vertical assignment flexibility by making the modules structurally similar allows any module with the same finish from the upper floor to be re-assigned to Slot 5. The benefit of this is that the installation would not be halted for any longer than it takes for a suitable upper floor module to arrive at the site.

Definition 9: Lateral assignment flexibility

Is the ability to install a module in a different slot from the one originally intended on the same floor.

Consider a variant of the base scenario where all modules have finish similarity when they arrive at the site. Should the module originally assigned for Slot 1 be disrupted, lateral assignment flexibility would allow any of the modules from slots 2 to 5 to be re-assigned in its place and as such minimise any delay in the installation process that would have otherwise occurred.

4.3.3 Slot installation sequence flexibility

Slot installation sequence flexibility is concerned with the order in which slots in the building are filled with modules.

Definition 10: Vertical sequence flexibility

Is the ability to install a module on an upper floor while a lower floor is not yet finished.

Consider a variant of the base scenario where each module is unique in terms of finish and hence can only be installed in its assigned slot. Should the module assigned to Slot 5 (the last slot on floor 1) be disrupted, vertical sequence flexibility would allow the installation process to continue on the upper floor for slots 6 to 9 as soon as they arrive rather than having to wait for the disrupted module.

Definition 11: Lateral sequence flexibility
Is the ability to install modules on the same floor in more than one slot installation sequence.

Consider a variant of the base scenario where each module is unique in terms of finish and hence can only be installed in its assigned slot. Should the module for Slot 3 be disrupted, enabling lateral sequence flexibility would allow subsequent modules on the floor to continue to be installed as soon as they arrive, leaving a gap at Slot 3. Consequently, the installation would only be further delayed if the disrupted module does not arrive by the time all other modules for that floor have been installed.

4.3.4 Motivation to study all four types of on-site installation flexibility

This section argues the need to study all four types of on-site installation flexibility given that the relative effectiveness of each may vary depending on disruption conditions and building configuration.

Consider the aforementioned base scenario where there are 10 *module types* (labelled A-J) each assigned to a given slot. Figure 4-4 shows three hypothetical building configurations corresponding to when: i) either lateral sequence flexibility, or vertical sequence flexibility, or no flexibility is enabled, ii) vertical assignment flexibility is enabled, or iii) lateral assignment flexibility is enabled. Given that no changes to module finish or structure are required to enable lateral or vertical sequence flexibility, the number of module types remains unchanged compared to having no on-site installation flexibility. However, in cases ii) and iii), assignment flexibility requires fewer module types.

When no disruptions occur, the installation process follows the nominal slot installation sequence which fills the slots numbered from lowest to highest. Modules are installed in the order in which they are produced: the first module produced (Module 1) is nominally installed in Slot 1, the second (Module 2) is nominally installed in Slot 2, and so on. Modules are assumed to take 1 time period to be installed when they are delivered to the site. Consequently, should no delay occur in their delivery, the installation takes a total of 10 time periods.

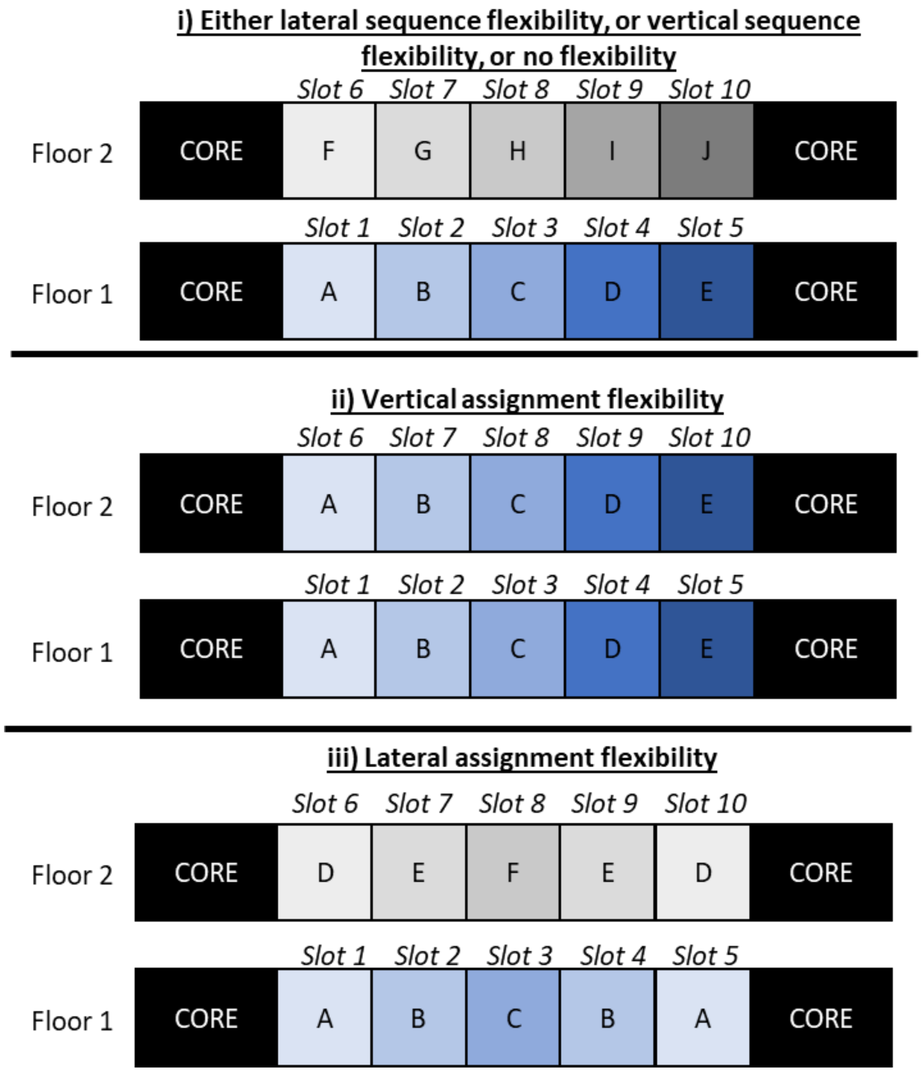

Figure 4-4: Building configurations showing the module type required by each slot depending on the level of on-site installation flexibility enabled. Similarities in module types are highlighted using colour shading.

Consider three different disruption scenarios: 1) the first module produced (Module 1) is delayed for 10 time periods, 2) the fifth module produced (Module 5) is delayed for 8 time periods, and 3) the sixth module produced (Module 6) is delayed for 5 time periods. Figure 4-5 shows the times at which each module is installed in the building for the different disruption scenarios for each flexibility type. The flexibility type that results in the shortest installation time (as highlighted in green) differs for each scenario.

Scenario 1: Module 1 delayed for 10 time periods

	Time period																				
Flexibility?	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Comment**
None											1	2	3	4	5	6	7	8	9	10	Installation is halted until Module 1 arrives.
VS											1	2	3	4	5	6	7	8	9	10	Upper floor modules cannot be installed until modules directly beneath them on Floor 1 have been installed. Hence VS in this instance makes no difference.
LS		2	3	4	5						1	6	7	8	9	10					LS allows the remaining four modules to be installed after which the installation is halted until Module 1 arrives as there is no vertical flexibility.
VA						6	2	3	4	5	1	7	8	9	10						VA allows installation to continue once Module 6 of type A arrives to fill Slot 1.
LA					5	2	3	4			1	6	7	8	9	10					LA allows Floor 1 to resume installation once Module 5 of type A arrives to fill Slot 1. Installation must halt again until the delayed Module 1 arrives to complete Floor 1.

Scenario 2: Module 5 delayed for 8 time periods

	Time period																				
Flexibility?	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Comment**
None	1	2	3	4									5	6	7	8	9	10			Installation is halted until Module 5 arrives.
VS	1	2	3	4		6	7	8	9				5	10							VS allows modules to be installed on Floor 2 even though Floor 1 is incomplete.
LS	1	2	3	4									5	6	7	8	9	10			LS is of no help given that Module 5 is the last module on Floor 1 to be installed.
VA	1	2	3	4						10	6	7	8	9	5						VA allows installation to continue once Module 10 of type E arrives and is installed in Slot 5.
LA	1	2	3	4									5	6	7	8	9	10			LA is of no help given that Module 5 is the last of Type A to be produced.

Scenario 3: Module 6 delayed for 5 time periods

	Time period																				
Flexibility?	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Comment**
None	1	2	3	4	5						6	7	8	9	10						Installation is halted until Module 6 arrives.
VS	1	2	3	4	5						6	7	8	9	10						VS is of no help given that Floor 2 is the last floor.
LS	1	2	3	4	5		7	8	9	10	6										LS allows modules to continue to be installed on the upper floor in wait of Module 6.
VA	1	2	3	4	5						6	7	8	9	10						VA is of no help given that there are no further floors from which modules can be re-assigned.
LA	1	2	3	4	5					10	7	8	9	6							LA allows installation to continue by re-assigning Module 10 to Slot 6.

= Module number

Figure 4-5: Time at which the modules were installed for each disruption scenario for different levels of on-site installation flexibility (VA = Vertical assignment flexibility; LA = Lateral assignment flexibility; VS = Vertical sequence flexibility; LS = Lateral sequence flexibility).

Next consider a building configuration where a greater degree of lateral assignment flexibility is enabled by having only one module type per floor, as shown in Figure 4-6.

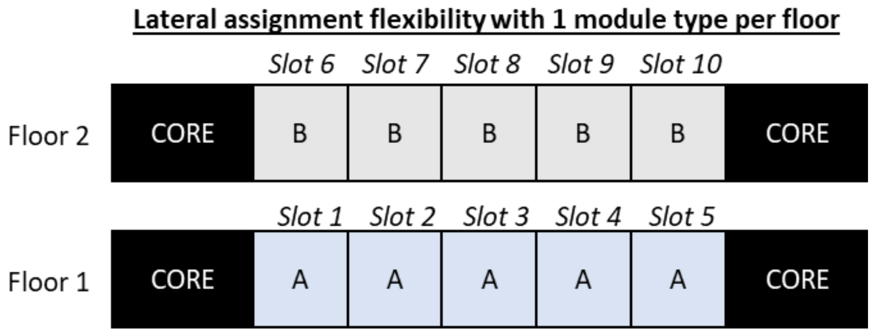

Figure 4-6: Building configuration for lateral assignment flexibility with one module type per floor. Similarities in module types are highlighted using colour shading.

Figure 4-7 shows the resulting effectiveness of each flexibility option for a fourth scenario where Module 1 is delayed for 5 time periods. Lateral sequence and assignment flexibility perform equally well. That said, even though both result in the same total installation time, the sequence in which the slots are filled differs. With lateral sequence flexibility, modules are installed in slots 2 to 5 before Slot 1 is filled. With lateral assignment flexibility, the modules nominally assigned to slots 2 to 5 are instead re-assigned to slots 1 to 4 after which the delayed module is installed in Slot 5. This brings home that even though the total installation time is the same, the sequence in which the slots are filled differs. This difference in slot installation sequence may have an impact on the relative effectiveness of different flexibility combinations (i.e. having more than one on-site installation flexibility enabled at the same time). To conclude, it is of interest to study the relative performance of different on-site installation flexibilities and their combinations.

Scenario 4: Module 1 delayed for 5 time periods

	Time period																				
Flexibility?	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**Comment**
None						1	2	3	4	5	6	7	8	9	10						Installation is halted until Module 1 arrives.
VS						1	2	3	4	5	6	7	8	9	10						Upper floor modules cannot be installed until modules directly beneath them on Floor 1 have been installed.
LS		2	3	4	5	1	6	7	8	9	10										LS allows the installation on Floor 1 to continue while awaiting Module 1.
VA						1	2	3	4	5	6	7	8	9	10						VA is of no help given that there are no modules from upper floors that can be re-assigned.
LA		2	3	4	5	1	6	7	8	9	10										LA allows modules on Floor 1 to be re-assigned to allow installation to continue.

\# = Module number

Figure 4-7: Module installation times for different levels of flexibility (VA = Vertical assignment flexibility; LA = Lateral assignment flexibility; VS = Vertical sequence flexibility; LS = Lateral sequence flexibility).

4.3.5 Summary

To summarise, four different types of on-site installation flexibility were proposed. Each targets one of the on-site installation constraints. The relative performances of each type of on-site installation flexibility are dependent on the disruption conditions and the building configuration. Hence, it is of value to study all flexibility types given that there is no single best performing one in all disruption scenarios. The next section investigates the practicalities of enabling on-site installation flexibility.

4.4 Enabling on-site installation flexibility

This section is concerned with investigating how on-site installation flexibility can be enabled. To begin, the methodology that was adopted to help address the four objectives of this chapter is described. Next an overview is given of the enablers (i.e. the practical steps or changes that a company has to implement to enable each on-site installation flexibility) that were identified for each flexibility type. From these, the implementation roadmaps created for each on-site installation flexibility type are presented. Finally, a series of managerial implications are put forward based on an analysis of the enablers and their interdependencies. Figure 4-8 shows an overview of this section.

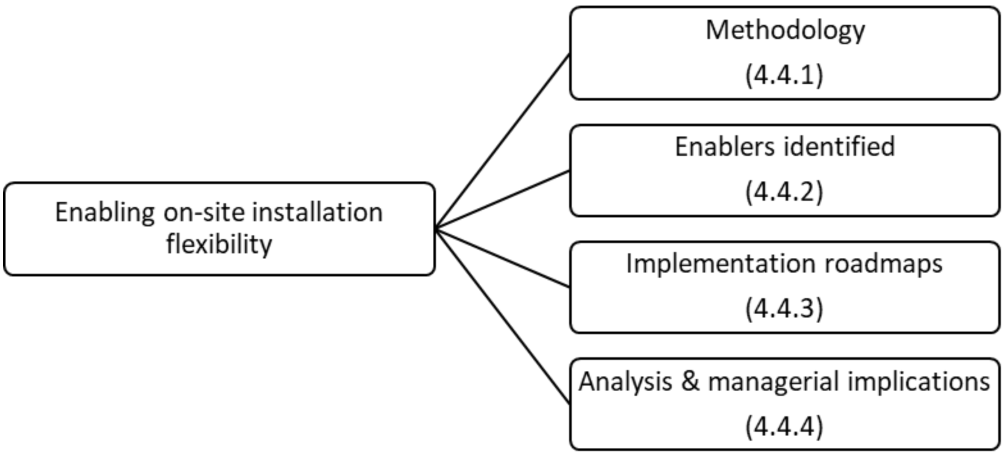

Figure 4-8: Overview of Section 4.4.

4.4.1 Methodology

To meet the objectives of this chapter, the methodology followed a mixed-method approach which leads to a better understanding of research problems (Creswell, 2009) because it combines the benefits of the different methods (Yilmaz, 2013). The methods chosen were a *workshop*[5], *Interpretive Structural Modelling* (ISM), and *Impact Matrix Cross-Reference Multiplication Applied to a Classification* (MICMAC) analysis. Table 4.1 shows the breakdown of the methodology and how each method contributed to accomplishing the objectives. An explanation of each method and a justification for why each was chosen is given next.

Table 4.1: Breakdown of the methodology and how each method contributes to addressing each objective.

	Qualitative methods	Quantitative methods	
Chapter 4 objective	**Workshop**	**MICMAC**	**ISM**
1. To define and validate the different types of on-site installation flexibility.	X		
2. To identify the different enablers of each type of on-site installation flexibility.	X		
3. To understand the interdependencies between the different enablers.	X	X	X
4. To create implementation roadmaps that show the order in which the enablers should be implemented.			X

A workshop is an effective way of obtaining the opinions of a range of experts with different expertise (Given, 2009) and was therefore chosen as a method to help address the first three objectives. With respect to objective 1, the greater the combined knowledge and experience of the experts who validated the four types of on-site installation flexibility, the greater the confidence in their validity. With respect to objectives 2 and 3, given that i) enablers were likely to span the breadth of functions and operations within an organisation, and consequently ii) the interdependencies would likely span across these functions, input from experts from a range of roles within a modular off-site construction company was of particular importance.

The workshop was conducted with employees of a large-multinational construction company that produces modular multi-storey buildings. The company was chosen for the following four reasons.

[5] Note that this is a different workshop to that organised and referred to in Chapter 3.

Firstly, all four types of on-site installation flexibility are applicable to the buildings produced by the company, which makes it well suited to fulfil objectives 1-4. Secondly, the company can produce buildings for a number of different end uses that have a range of finish similarities. Consequently, any identified enablers may be more broadly applicable to other companies. Thirdly, the company has a base in the UK which minimises time and cost of this research whilst maximising returns. Fourthly, with all the participants being from a single company, it meant that they were more willing to discuss and share potentially sensitive information than they might have been in a wider forum. Employees from across a wide range of business functions were invited to attend. In total 5 experts took part which is within the range recommended by (Kapse *et al.*, 2018). Their professional backgrounds are detailed in Table 4.2.

Table 4.2: Professional background of experts who took part in the workshop.

	Job title	Years of experience in Construction
1	Modular Off-site Construction Project Leader	15
2	Modular Off-site Construction Planning Leader	13
3	Modular Off-site Construction Technical Leader	15
4	Modular Off-site Construction Product Development Leader	10
5	Modular Off-site Construction Researcher	4

During the workshop three things were accomplished: i) the four on-site installation flexibility types were validated; ii) the enablers of each flexibility were identified and grouped according to business function to which they belong; and iii) their interdependencies were captured. Similarly to Chapter 3's workshop design (see section 3.2.2), the design of the workshop was adapted from the steps outlined in (Knodel, 1993; Nyumba *et al.*, 2018) and is shown in Table 4.3.

Table 4.3: Workshop procedure.

Step	Tasks	Sub-tasks
Preparation	Define the objectives of the study	
	Select workshop participants	Determine criteria to select the participants Short-list participants Contact participants
	Create background information for the participants	Create props to visually explain the different types of on-site installation flexibility to participants Preliminary brainstorming of enablers and their interdependencies
	Ensure material supports are available and functioning	
Data collection	Facilitation	Participant introduction Overview of research presentation Ensure participants understand what is required Validate the proposed types of on-site installation flexibility Discuss practicalities of implementing on-site installation flexibility Discuss interdependencies when unlocking each enabler
Data analysis	Summarise findings from the workshop	

To achieve objectives 3 and 4, it was necessary to use quantitative methods capable of analysing the complex interdependencies. To this end, several methods were evaluated and ISM and MICMAC were selected. A detailed explanation and justification for this is given in Appendix B.1.1.

The ISM method outputs an implementation roadmap by creating a hierarchy of enablers based on how many other enablers they directly or indirectly influence. The details of how ISM works are explained in Appendix B.1.2. MICMAC analyses the driving power (i.e. how much an enabler influences the enablement of another) and dependence power (i.e. how much an enabler is influenced by another) of the different enablers influencing a system (Kapse *et al.*, 2018). It classifies enablers into one of four categories in accordance with (Raj, Shankar and Suhaib, 2008):

1. **Autonomous enablers**: are those that have a weak driving and dependency power. They are relatively disconnected from the rest of the enablers.
2. **Dependent enablers**: are those with a low driving power but high dependence power. Consequently, they are influenced by the decisions made on other enablers that are enabled before them.

3. **Linkage enablers**: are those with high driving and dependence power. Any action on them will influence others above and below in the hierarchy.
4. **Independent enablers**: are those with high driving power but low dependence power. They are often referred to as "key enablers" as they often influence all other enablers.

These classifications help understand the relative influence of each enabler and the trends in the influence of the different business functions to which each belongs. It is important to note that the category to which an enabler belongs does not imply that some are less critical to the enablement of each flexibility. Rather, it gives a sense of the order in which each enabler should be considered when implementing a given flexibility. Further details on the MICMAC method are presented in Appendix B.1.3.

To summarise the above, Figure 4-9 shows an overview of the different steps in the methodology and how they map onto the objectives of this chapter (see Appendix B.1.4 for a detailed flowchart).

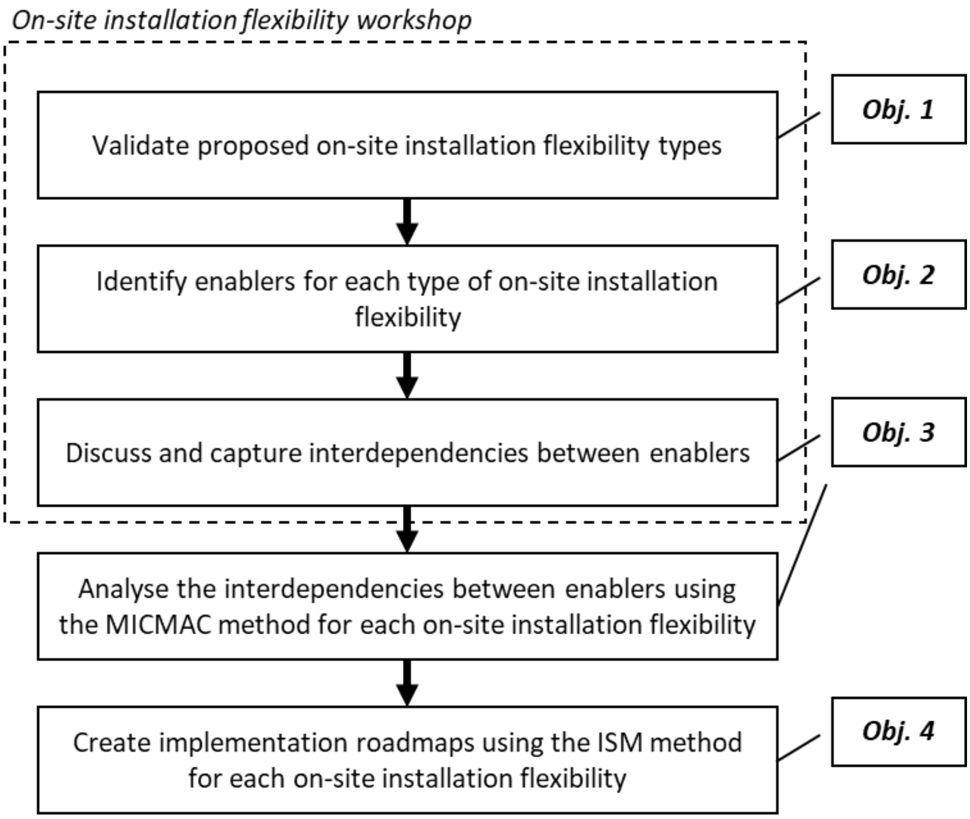

Figure 4-9: Summary of the methodology used in Chapter 4.

4.4.2 Overview of the enablers of the on-site installation flexibilities

A comprehensive set of 56 enablers was identified through the workshop with modular off-site construction experts, as shown in Table 4.4. Each row in Table 4.4shows whether a given enabler is required for each type of on-site installation flexibility. Practitioners can make use of this list as a starting point when they consider the enablers required to implement on-site installation flexibility in their organisations. Further details about each enabler and the rationale as to why it was found to be required for a given type of installation flexibility are given in the Appendix Table B.2.

Table 4.4: Mapping of enablers identified during the workshop to different types of installation flexibility. Green = required; Red = not required.

ID	Business function	Enabler	Sequence flexibility		Assignment flexibility	
			Vertical	Lateral	Vertical	Lateral
1	Construction site	Update quality assurance protocol at site				
2		Availability of additional site personnel to install modules				
3		Availability of additional site personnel to complete module exterior				
4		Availability of adequate number of craftsmen to finish modules at the site				
5		Availability of adequate lifting equipment for facilitating movement of material				
6		Adequate number of on-site facilities				
7		Availability of adequate tools at the site				
8		Create on-site standard operating procedures				
9		Train site personnel with new methods of installation				
10		Jump crane to height capable of reaching all areas of the building from start of project				
11		Erect temporary works to support the crane				
12		Availability of cranes with adequate span from start of build				
13		Availability of crane with adequate lifting strength				
14		Accurate crane path control				
15	Design	Alter module connector design				
16		Re-design load bearing portions of the modules				
17		Design "safety walkway" to cover empty slots				
18		Standardise fire compartmentalisation of modules				
19		Standardise module structures				
20		Strengthen building foundations				
21		Design floorplan column grid to allow modules to be re-assigned to any appropriate location				

ID	Business function	Enabler	Sequence flexibility		Assignment flexibility	
			Vertical	Lateral	Vertical	Lateral
22	Design	Design sufficient spacing between modules				
23		Increase the range of acceptable installation tolerances				
24		Standardised balcony fastening mechanism				
25		Standardised façade fastening mechanism				
26		Design modules such that their load bearing columns can attach anywhere on the floorplan				
27	Factory	Create off-site standard operating procedures				
28		Update manufacturing process				
29		Install adequate factory automation				
30		Train factory labour				
31		Availability of factory labour				
32		Availability of adequate tools at the factory				
33		Ensure the production line is balanced				
34		Availability of modules whose interior is finished to a common level at the point they leave the factory				
35		Existence of modules of identical exterior appearance when they leave the factory				
36	Financial	Funds for construction site changes				
37		Funds for factory changes				
38		Funds for design changes				
39	IT Infrastructure	Real time site installation sequence and module slot assignment updates				
40		Adequate IT infrastructure				
41		Real time on and off-site system status monitoring				
42	Legal	Update building regulations pack				
43		Acquire relevant building standard certifications				
44		Adequate H&S procedures				
45		Permission to build on all areas of the construction site from the start of the project				
46	Management	Top management support				
47		Effective communication with the site				
48		Client agreement				
49		Strategic planning				
50		Project management skills				
51		Effective scheduling				
52		Performance measurement				
53		Get support from the unions				

			Sequence flexibility		Assignment flexibility	
ID	Business function	Enabler	Vertical	Lateral	Vertical	Lateral
54	Supply chain	Set up supply chain logistics for module design changes				
55		Set up supply chain for "safety walkway" production				
56		Set up supply chain to ensure appropriate material is delivered to the site				

4.4.3 On-site installation flexibility implementation roadmaps

Figure 4-10 shows the implementation roadmap for vertical sequence flexibility. The corresponding roadmaps for the remaining on-site installation flexibilities are given in the Appendix B.4. The roadmaps can be interpreted as follows. Enablers should be unlocked progressively, starting with those at the bottom of the roadmap and ending with those at the top. For instance, all roadmaps begin by requiring the practitioners to obtain “Top management support” to implement the various on-site installation flexibilities and the enablers that they require. In the case of vertical sequence flexibility, practitioners should unlock “Update new quality assurance protocol at site”, “Availability of adequate tools at the factory”, “Ensure the production line is balanced”, “Set up supply chain for safety walkway production”, and “Accurate crane path control” last as they are at the top of Figure 4-10.

The enablers of higher levels cannot be unlocked without enabling those of lower levels. The arrows connecting various enablers also indicate interdependencies between enablers. For instance, in Figure 4-10, “Design sufficient spacing between modules” (Level 7) requires “Funds for design changes” to be completed before (Level 4). The value of the roadmap produced using the ISM method is that it has greatly simplified the interdependencies captured during the workshop into an easy-to-follow set of instructions for practitioners. They can now use them as a guide when implementing on-site installation flexibility within their organisation.

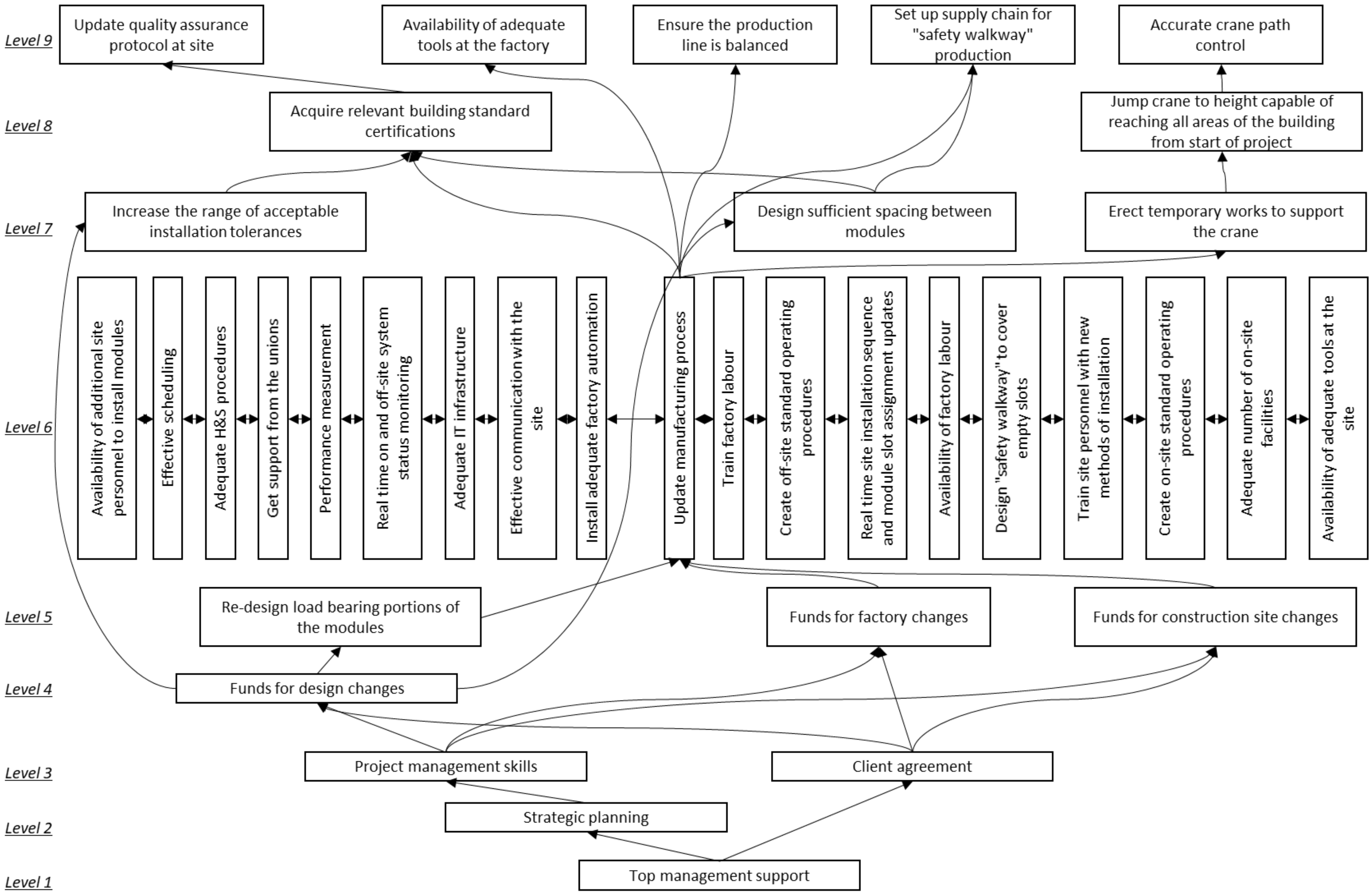

Figure 4-10: Vertical sequence flexibility implementation roadmap (ISM model).

4.4.4 Analysis of the enablers and managerial implications

Figure 4-11 shows that each on-site installation flexibility type requires many enablers – between 35 and 42 of the 56 identified enablers. What is more, each flexibility type requires changes in many of the business functions of the organisation. That said, most of the enablers belong to just three of the eight business functions: "Factory", "Management", and "Construction site". On average, they represent 61% of enablers required across the different installation flexibilities. Nonetheless, the breakdown by business function does vary from one flexibility type to another. For instance, for vertical assignment flexibility, "Design" enablers make up 17% of its enablers compared to 11%-13% for the other on-site installation flexibility types. This is because more design changes are required as a result of needing to make the structure of the modules similar so that they can bear the load whichever floor they are installed on. "Construction site" enablers account for a greater proportion for vertical sequence flexibility (24% compared to 16-17% for the other flexibility types). This is because of extra labour requirements and crane set up modifications to ensure modules can be installed on an upper floor while a lower floor is not yet finished.

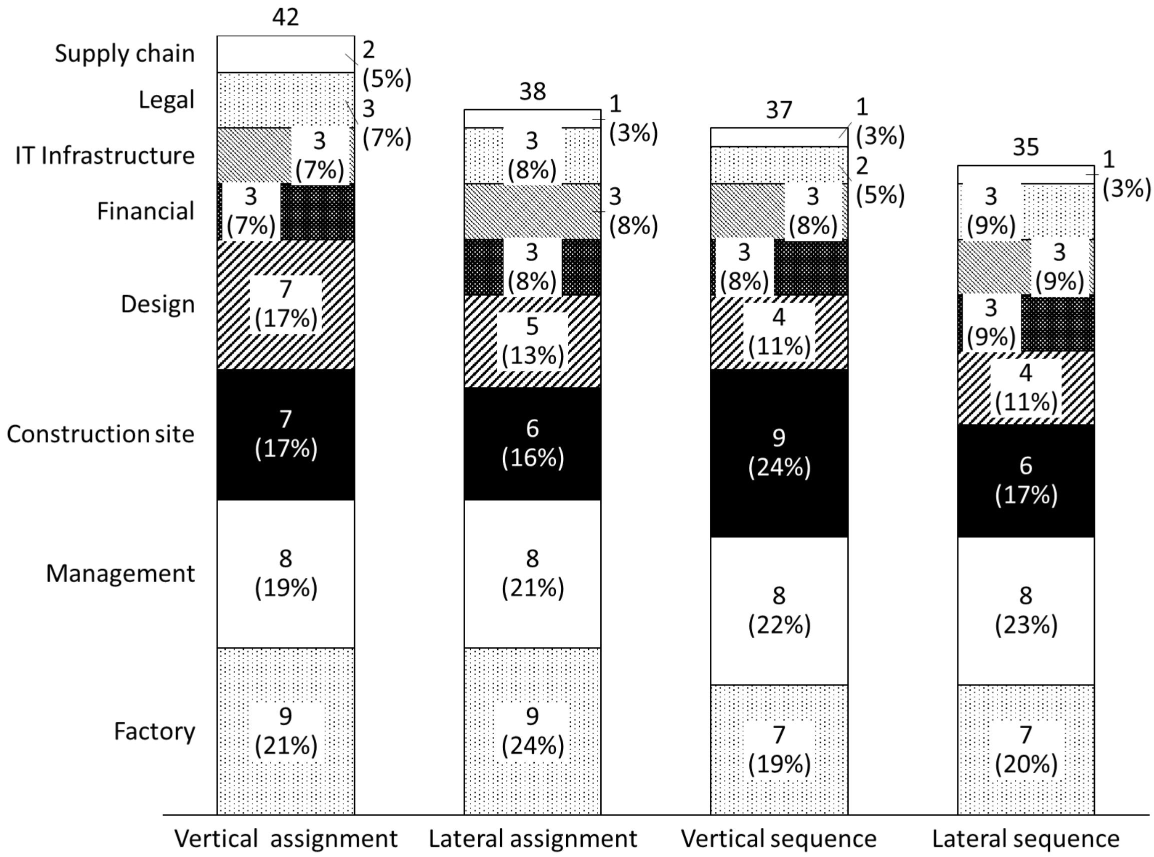

Figure 4-11: Breakdown of enablers by business functions for each on-site installation flexibility type (the proportions of enablers belonging to the different categories for a given flexibility type are shown in brackets).

Managerial implication: *Each type of on-site installation flexibility requires a unique combination of many enablers across the breadth of the organisation.*

Figure 4-12 shows that most enablers (80%) identified by the experts are required by at least two installation flexibility types. Furthermore, a large proportion (45%) are common across all four installation flexibility types. Indeed, the same “Management”, “Financial”, and “IT infrastructure” enablers were required regardless of installation flexibility type. This is of interest as experts mentioned that cost efficiencies could be achieved when implementing more than one installation flexibility type as the work to implement a common enabler would only have to be done once.

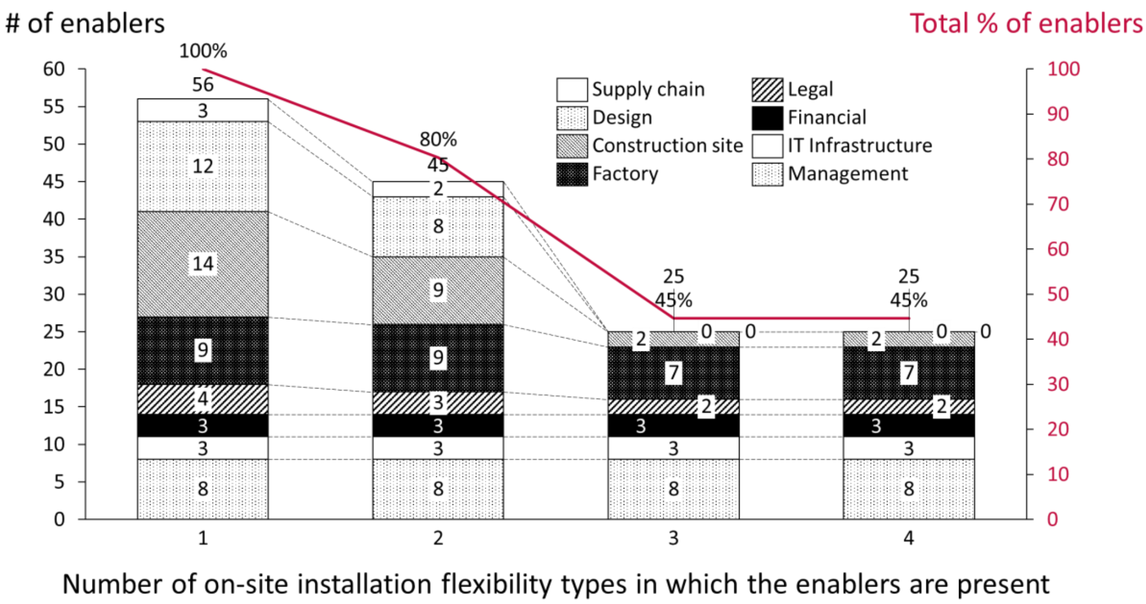

Figure 4-12: Commonality of enablers across installation flexibility types.

Managerial implication: *Given that some enablers are common across several installation flexibility types, cost efficiencies can be achieved when implementing more than one flexibility at the same time.*

An analysis of the percentage of enablers that are common between different flexibility types was undertaken. The average commonality between the enablers of each flexibility type is 75.5%. What is more, the average degree of commonality between flexibilities of the same overarching type (i.e. either slot installation sequence flexibility or slot assignment flexibility) is 91% whereas that for different overarching types is 68%. As such, larger implementation cost efficiencies could be expected if practitioners implement both the lateral and vertical variants of a given type of installation flexibility at the same time.

Managerial implication: *Greater cost efficiencies can be expected when implementing at the same time both the lateral and vertical variants of either slot assignment or slot installation sequence flexibility.*

Figure 4-13 shows the number of enablers per MICMAC category (see Section 4.4.1 where they were defined) for each of the installation flexibility types. Autonomous enablers represent a minor proportion, 9% at most, of enablers across all on-site installation flexibilities. This brings home the high level of interdependencies between the enablers of on-site installation flexibility. Hence practitioners should carefully consider the impact of the decisions made when implementing each enabler.

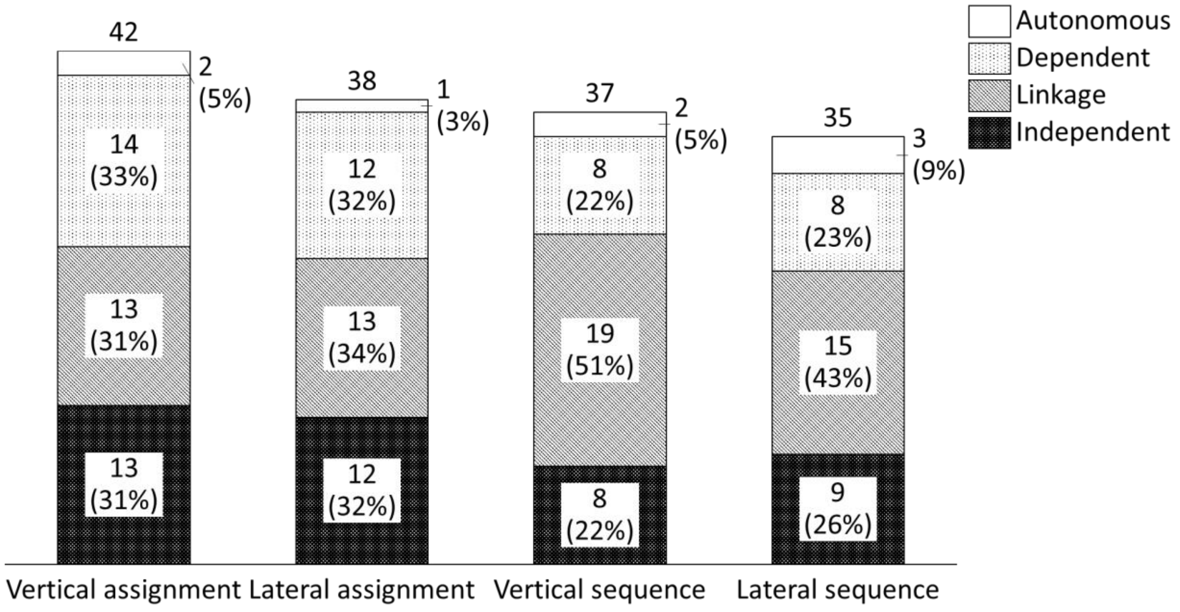

Figure 4-13: MICMAC category analysis.

Managerial implication: *Care should be taken when implementing each enabler given the high degree of interdependency between them.*

The MICMAC analysis determined that enablers almost always belong to the same MICMAC category across all types of installation flexibility[6]. As such the implementation sequence remains relatively the same across the different flexibility types. Generally, the different MICMAC categories of enablers are implemented in the following order: Independent, Linkage, then Dependent, while Autonomous can appear at various levels in the sequence. Figure 4-14 shows that "Financial", "Design", and "Management" enablers are primarily classed as Independent. These should be the first to be unlocked to progress to enablers belonging to other business functions. This makes sense given that without Independent enablers such as "Top management support" or "Funds for construction site changes", it is not possible to progress further with implementation of installation flexibilities. Linkage enablers can be found in six out of the eight business functions. This implies that in the middle of the implementation process, a great deal of co-ordination will be required between business functions when making decisions on the enablers. Enablers that belong to the "Construction site", "Legal", and "Supply Chain" functions were found primarily to be Dependent enablers. This is because a lot of the changes in these business functions depend on the enabler decisions already made further upstream.

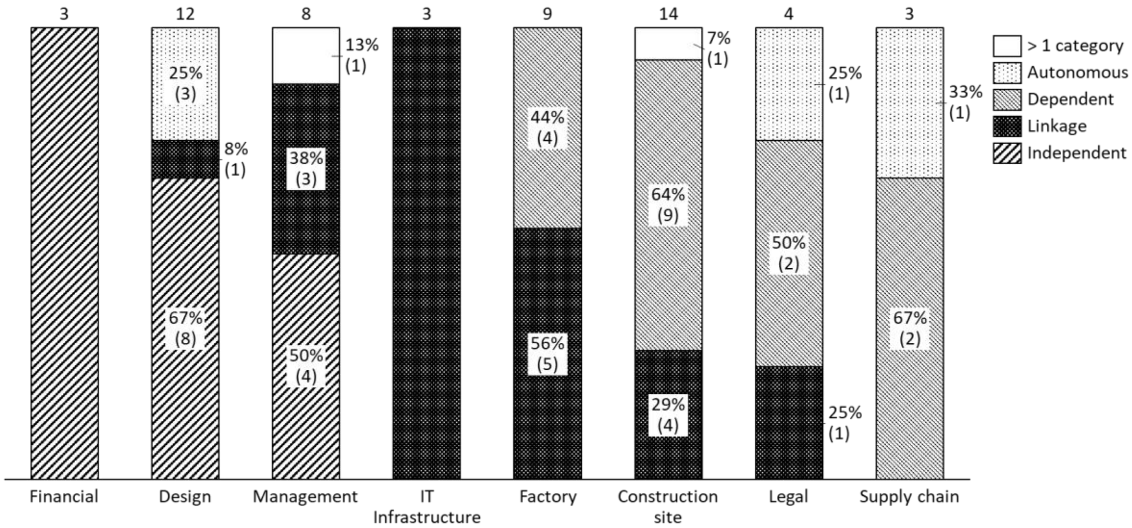

Figure 4-14: Breakdown of MICMAC categories per enabler category.

<u>Managerial implication:</u> *Different functions in the business take part at different stages of the on-site installation flexibility implementation process. Some are predominantly involved at the start, some at the end, while those in the middle require co-ordination between many business functions.*

[6] Two exceptions to this were "Adequate number of on-site facilities" and "Effective communication with the site" that were classed as Linkage enablers for vertical sequence flexibility but as Dependent enablers for other flexibility types.

4.5 Summary

This chapter set out to achieve four objectives:

1. To define and validate the different types of on-site installation flexibility.
2. To identify the different enablers of each type of on-site installation flexibility.
3. To understand the interdependencies between the different enablers.
4. To create implementation roadmaps that show the order in which the enablers should be implemented.

Four types of on-site installation flexibility were proposed and their benefits were explained in the context of a range of different disruptions. The flexibilities were subsequently validated by experts – accomplishing objective 1. 56 different enablers were identified in a workshop that was organised to understand what was required to implement each type of installation flexibility – completing objective 2. Practitioners can now make use of this list as a starting point when they consider the enablers required to implement on-site installation flexibility in their organisations. To fulfil objective 3, the enablers were further analysed in combination with a MICMAC analysis from which the following managerial implications were identified:

1. Each type of on-site installation flexibility requires a unique combination of many enablers across the breadth of the organisation.
2. Given that some enablers are common across several installation flexibility types, cost efficiencies can be achieved when implementing more than one flexibility at the same time.
3. Greater cost efficiencies can be expected when implementing at the same time both the lateral and vertical variants of either slot assignment or slot installation sequence flexibility.
4. Care should be taken when implementing each enabler given the high degree of interdependency between them.
5. Different functions in the business take part at different stages of the on-site installation flexibility implementation process. Some are predominantly involved at the start, some at the end, while those in the middle require more co-ordination between many business functions.

Implementation roadmaps for each type of on-site installation flexibility were developed through Interpretive Structural Modelling – completing objective 4. Practitioners can make use of the implementation roadmaps to guide them through the stages of implementing on-site installation flexibility.

Next in Chapter 5, a model is developed to analyse how the availability of on-site installation flexibility affects the behaviour of modular off-site construction systems. In addition, an approach to aid decision makers in selecting the appropriate level of on-site installation flexibility in combination with other disruption management strategy investments is presented.

Chapter 5:
Selecting on-site installation flexibilities for disruption management

5.1 Introduction

On-site installation flexibility is a newly proposed way to help manage disruptions. The management (referred to as decision makers) of a modular off-site construction company are faced with the challenge of deciding whether to implement one or more types of on-site installation flexibility when alternative disruption management strategies are available to minimise costs during the installation phase of the project. The focus of this chapter is on developing an approach to aid decision makers answer this problem. The objectives of this chapter are to:

1. Formally describe the problem faced by decision makers as to whether on-site installation flexibility should be enabled.
2. Specify the requirements of any modelling approach to address the problem.
3. Compare and evaluate different modelling approaches which could be developed.
4. Develop a model that determines the optimal level of on-site installation flexibility when weighed against alternative disruption mitigation options.
5. Describe an approach that draws from findings obtained in Section 4.4 (the identified enablers and potential cost efficiencies in enabling more than one on-site installation flexibility) and incorporates the above-mentioned model to facilitate decision-making.

Section 5.2 provides a formal description of the problem faced by decision makers regarding the level of on-site installation flexibility that should be enabled when alternative disruption mitigation options are available. Next, in Section 5.3 a justification for the methodology that was adopted to address this problem is given in overview. A Simulation-Based Optimisation model to address the problem is then detailed in Section 5.4. Finally, a decision-making approach in which the model is incorporated is described in Section 5.5.

5.2 Problem statement

In this section, the problem of what level of on-site installation flexibility to enable when balanced against other disruption management options in view of minimising project costs is formally defined.

Consider a modular off-site construction project that consists of manufacturing and assembling a building. The building is made up of a set of modules, $M = \{1, \dots, m, \dots, N_m\}$, where N_m is the total number of modules in the building. Each module can be categorised as a specific type, u, which belongs to the set of types $U = \{1, \dots, u, \dots, N_{type}\}$, where N_{type} is the total number of module types. All modules of a given module type are identical and can therefore be assigned to any slot requiring that type.

Figure 5-1 delineates the areas of the off-site construction process that this research considers. The modules are manufactured in a factory that produces one module every $t_{factory}$ time units in accordance with the production sequence Seq_{prod}, which is an ordered set of module indices m. The production sequence matches the nominal module installation sequence, Seq_{minst}, which is the planned sequence in which modules are installed at the site. When a module exits the factory production line, it spends t_{qa} time units at the quality assurance station that checks for any defects or uncompleted work as a result of Type 1 disruptions inbound to and at the factory (see Figure 4-1). A module is sent for re-work[7] should it fail the quality assurance. From the point of view of the on-site installation operations, this means that each module can be viewed as having a certain probability of disruption for a certain duration. Because of their stochastic nature, these disruptions introduce uncertainty in the behaviour of the system. After the re-work has been completed, modules are transported to the site and stored (if necessary) in a buffer t_{fb} time units away. Subsequently, modules are installed following the precedence defined in the nominal module installation sequence Seq_{minst} when possible. These modules are installed in slots following the nominal slot installation sequence Seq_{sinst}. Installation of a module takes t_{crane} time units.

[7] Re-work is assumed to be used by companies as: i) if damaged, too much added value is tied up in the module for it to be scrapped, and ii) if material for the module is delayed, the cost of holding up the production line is too great.

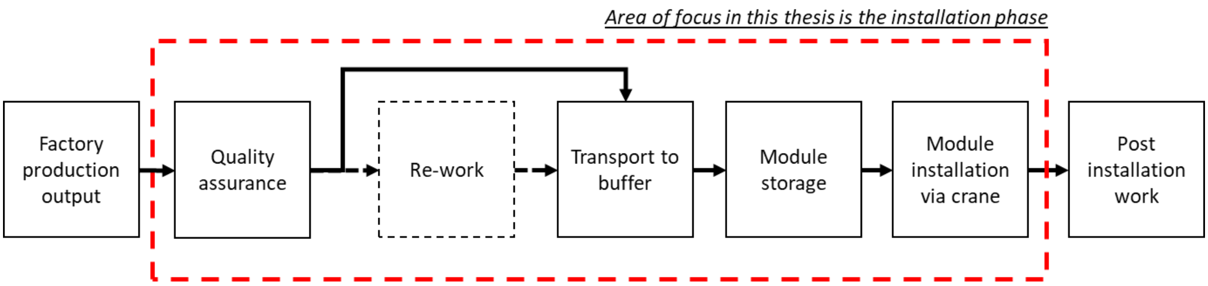

Figure 5-1: Flow chart of off-site system under consideration.

The challenge at the project design stage for decision makers is to decide on the level of on-site installation flexibility to enable when balanced against other disruption management options to minimise the cost of the installation phase. It is important to consider other disruption management options for three reasons. Firstly, it more accurately reflects the opportunity cost faced by decision makers when considering whether to enable on-site installation flexibility. Secondly, it has been shown that investing too heavily in a single strategy may outweigh the benefits (Kesavan, Staats and Gilland, 2014). Thirdly, certain combinations of different disruption management strategies may not always be beneficial (Goyal and Netessine, 2011). It is inevitable for companies to have other disruption management strategies in place. These three reasons will have a bearing on the most appropriate level of on-site installation flexibility to enable (RQ3). Hence, other disruption management options are important to consider when making the decision. Given the wide range of disruption management strategies practitioners can choose instead of or in conjunction with on-site installation flexibilities, this research will limit itself to only a few based on the findings in Table 3.6 and in consultation with practitioners:

- **Permanent and emergency storage buffers:** Using storage as a management strategy was the most commonly cited method to counter upstream disruptions, as shown in Table 3.6. From discussions with practitioners, companies want to avoid halting the production line at all costs and hence will always make use of at least an emergency buffer should need be. Alternatively, practitioners may decide to invest in a permanent storage buffer of a size of their choosing. Any overflow is then stored at a premium cost in an emergency storage buffer to ensure that the factory never comes to a halt.
- **Disruption mitigation options that reduce either the likelihood or the duration of potential disruptions**: There are several disruption management strategies (e.g. see Table 3.6) that have the benefit of either reducing the likelihood a module is disrupted (e.g. risk management built into contracts) or the duration a module is disrupted (e.g. substituting a component with a similar one). The specific way this reduction is achieved is less important in investigating this problem than the broader impact of utilising such a disruption management approach.

5.3 Methodology

A quantitative approach was chosen given that the problem involves costs, and uncertainties concerning disruptions and decisions to be made. A model was developed following the methodology proposed in (Sargent, 2013)[8], which has been shown to be a valid approach for modelling off-site construction systems (Mostafa, Chileshe and Abdelhamid, 2016). Figure 5-2 illustrates this methodology. There are three principal stages to developing a model:

1. The identification of the "Problem Entity (system)", which is the real-life system being analysed (i.e. a modular off-site construction system).
2. The description of the "Conceptual Model", which is the mathematical/logical/verbal representation of the Problem Entity. Section 5.2 above describes the Conceptual Model.
3. The development of the "Computerised Model", which is the implementation of the Conceptual Model on a computer. The requirements of the Computerised Model are identified in Section 5.4.1. A range of modelling techniques to build the Computerised Model is evaluated in Section 5.4.2, and the selected technique is then described in Section 5.4.3.

At each stage, validation and verification must be undertaken to ensure that the findings are of practical use. This is detailed Section 5.4.4.

[8] Even though the paper is geared towards simulation-based modelling, it strongly resembles the key steps detailed in (Bertrand and Fransoo, 2002) for non-simulation-based models only that it has additional requirements for verification and validation of simulation models. As such the methodology was deemed appropriate regardless of whether a simulation or purely mathematical approach was adopted.

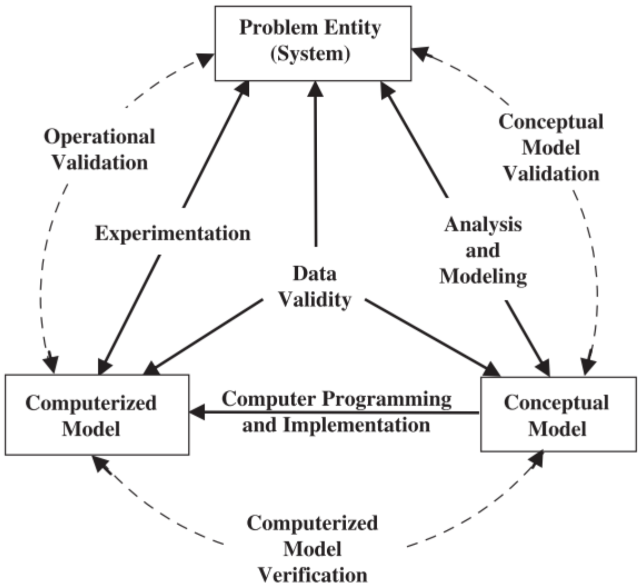

Figure 5-2: Modelling process (Sargent, 2013)**.**

Finally in Section 5.5, inspired by the methodology in (Padhi *et al.*, 2013), the Computerised Model is incorporated into an overall approach devised to aid practitioners to select the most appropriate level of on-site installation flexibility in possible combination with other investment options.

5.4 A Simulation-Based Optimisation model to select on-site installation flexibility level

5.4.1 Requirements of the modelling approach

To represent accurately the environment shown in Figure 5-1, it was necessary for the model to capture the constraints of real-life off-site construction systems. As such, using the observations in Section 5.2, the following constraints were identified:

1. Modules may not leave a resource (e.g. the quality assurance station) until the next resource in the process flow is free. As a result, the resource remains "blocked". In academic literature this is commonly known as the "blockage constraint" (Hall and Sriskandarajah, 1996; Tavakkoli-Moghaddam, Safaei and Sassani, 2009; Maleki-daronkolaei and Seyedi, 2013).
2. The on-site installation constraints defined in Section 2.3.4. Without on-site installation flexibility, off-site buildings must be assembled on site according to the fixed module installation sequence because of the on-site installation constraints. For example, modules for

the first floor may not be installed until those of the ground floor have been installed and must be stored until then. A similar constraint has been modelled mathematically in academic literature for concurrent shops (flow, job, etc.) where a job made up of several components can only be finished once all of its components are completed (Roemer, 2006). According to the problem definition above, the jobs are equivalent to a building and the components are equivalent to modules.

3. Each process can call on a finite set of resources (e.g. a lorry, a crane, a re-work bay).
4. A process may only commence on a module if the resource required for that process is available. This constraint has been modelled mathematically in resource constrained scheduling (also known as disjunctive scheduling) (Pape and Baptiste, 1998) and is referred to here as a “resource constraint”.
5. It may not be possible to interrupt certain processes once they have commenced (e.g. once the crane has started to install a module it will not pause mid-air until it has successfully completed the installation). This characteristic of a production system is modelled mathematically by introducing what are called “pre-emption constraints” (Chen, Potts and Woeginger, 1998).
6. Modules have certain processes that must be completed before another may commence. For example, the installation of a module by the crane may only commence after the module has been transported to the site. This has been modelled mathematically by introducing what are called “precedence constraints” (Lee *et al.*, 2012).
7. By the end of the installation time-frame, all modules must be fully completed and assembled on-site.
8. A process is only required to be completed once (assuming re-work is considered as a separate process).
9. The completion time for a process may not be negative.

The exogenous (independent) variables are entered as inputs into the model. Those concerned with costs incurred in the system are listed in Table 5.1 whereas those regarding the system environment are detailed in Table 5.2. Some variables may have a level of uncertainty associated with them. For example, the transport time to the buffer from the factory may be subject to delays caused by heavy traffic. The model should therefore be able to reflect this if it is an area of concern.

Table 5.1: Exogenous operational cost variables.

Location in system at which cost is incurred	Cost	Unit
Factory	Re-work cost, $C_{rework\_per\_time\_unit}$	Cost unit/time unit
Permanent storage buffer	Land cost for buffer for k modules, $C_{fixed\_perm\_storage_k}$	Cost unit
Permanent storage buffer	Security cost, $C_{var\_perm\_storage\_per\_time\_unit}$	Cost unit/time unit
Emergency storage buffer	Inventory/WIP storage, $C_{em\_storage\_per\_module\_time\_unit}$	Cost unit/module/time unit
Project	Project delay penalty, $C_{delay\_per\_time\_unit}$	Cost unit/time unit

The endogenous (dependent) variables are created as a result of running the model. They can either describe the state or act as the objective function of the system. Several endogenous variables may be envisaged:

1. The delay caused by a disruption.
2. The dwell time of modules in the buffer.
3. The maximum number of modules in the buffer.
4. The percentage of modules that change from their nominal position in the module installation sequence.
5. The percentage of slots that change from their nominal position in the slot installation sequence.
6. The total floor completion delay, which is the sum of the delays in completing each floor in a building.

Table 5.2: Exogenous system environment variables.

Exogenous variable	Level of uncertainty	Unit
The set of modules produced M	No uncertainty	-
The set of module types U	No uncertainty	-
The nominal production sequence Seq_{prod}	No uncertainty	-
The nominal module installation sequence Seq_{minst}	No uncertainty	-
The nominal slot installation sequence Seq_{sinst}	No uncertainty	-
The nominal installation due time of each module	No uncertainty	Time unit
The nominal installation phase duration of project	No uncertainty	Time unit
Quality assurance process duration t_{qa}	Potentially uncertain	Time unit
Transport time to buffer from factory t_{fb}	Potentially uncertain	Time unit
Installation time at site by crane t_{crane}	Potentially uncertain	Time unit
Disruption duration	Potentially uncertain	Time unit
Probability a module is disrupted	No uncertainty	-
The paths between the various resources in the network	No uncertainty	-

In terms of the objective function that is used to evaluate the performance of the different combinations of on-site installation flexibilities and other disruption management options, cost saving is used as the primary measure of performance.

Some initial simplifying assumptions are made:

1. There are no set-up times between processes.
2. The system is in continuous operation.
3. The system experiences no disruptions other than modules requiring re-work.
4. All modules occupy the same amount of space.

In summary, based on the problem description and requirements listed above, the model should satisfy the following criteria:

Criterion 1: Reflect the operational behaviour of off-site construction systems by adequately capturing their constraints.

Criterion 2: Represent the uncertainty in the occurrence of random events such as whether a module is disrupted.

Criterion 3: Provide quantitative insight into the behaviour of off-site systems enabled by on-site installation flexibility in a reasonable computation time.

Criterion 4: Result in the selection of the (near-)optimal level of on-site installation flexibility weighed against alternative disruption management options.

5.4.2 Evaluation of different modelling techniques

Four potential categories of techniques for modelling the problem were identified: analytical, meta-heuristic, simulation-based, and Simulation-Based Optimisation (SBO). The full detailed analysis and discussion regarding the suitability of each to meet the four criteria is reported in Appendix C.1. In this section, only the justification for the adopted method of a two-stage SBO is presented.

SBO has been used to replicate complex real-world production environments and their constraints (Frantzén, Ng and Moore, 2011) and has proved to be highly successful in doing so (Syberfeldt *et al.*, 2009). A two-stage SBO combines a simulation-based technique with an analytical or meta-heuristic technique, called an *optimiser*, with the aim of overcoming their individual shortcomings (Diaz, Handl and Xu, 2018). The *simulation model* of the SBO serves to evaluate the performance of the system under a given set of conditions or parameter settings. The outputs of the simulation model are then used as inputs to the *optimiser*. The optimiser identifies the (near-) optimal solution to the problem.

In this case, a Discrete Event Simulation (DES) technique was chosen as the simulation model and Integer Linear Programming (ILP) as the optimiser. The DES model was first used to approximate the complex behaviour of the modular off-site construction system subject to its constraints (Criterion 1) as well as its uncertainty (Criterion 2). Provided the number of different combinations of on-site installation flexibility with disruption management options was not too time-consuming to evaluate, it fulfilled Criterion 3. The system performance values generated for each combination were subsequently input into the ILP which then selected the best performing combination (Criterion 4).

The benefits of using a DES technique is that it does not require as many simplifying assumptions to model real world operations as standard mathematical methods (Juan *et al.*, 2014). Furthermore, it is particularly well suited for cases where some factors are random variables which interact with each other and may be difficult to incorporate in a meaningful way in an analytical model (Srivastava *et al.*, 1989). It is also an accepted method to approach problems set in environments where there are many constraints (Ribas, Leisten and Framinan, 2010), which is certainly the case here. What is more, it scales better to larger problem instances (Juan *et al.*, 2014), meaning it is feasible to fulfil Criterion 3. In addition, it can be used to reinforce and facilitate managerial decision making processes, conduct experiments without disrupting system operation, and easily gain insight into different scenarios (Chou, Yang and Chong, 2009). Finally, Integer Linear Programs have frequently been used to investigate the benefits of various types of flexibility as they can compare many choices between different options according to a defined objective function (Jordan and Graves, 1995; Romero *et al.*, 2003; Tomlin, 2006; Ferrer-Nadal, Puigjaner and Guillén-Gosálbez, 2008; Kuzgunkaya and ElMaraghy, 2008; Hopp, Iravani and Xu, 2010). Next the exact details of the SBO model that was created are presented.

5.4.3 The Simulation-Based Optimisation model

In this section, a two-stage SBO model created by combining an ILP and a DES model is presented. The SBO model outputs the optimal combination of disruption mitigation options and on-site installation flexibilities that results in the greatest cost savings. The purpose of the ILP and the DES and how they interact with one another is explained next.

The purpose of the ILP is to select the combination of the disruption mitigation option combination i, on-site installation flexibility combination j, and permanent storage buffer capacity level k that results in the greatest cost savings. It is formulated as follows.

Given the stochastic nature of the disruptions, a distribution of cost savings, S_{ijk}, for each combination is to be expected. This variability is undesirable for decision makers who seek certainty in their decisions. Inspired by (Tomlin, 2006), variability is penalised in the objective function of the ILP by considering not only the median, $median(S_{ijk})$, but also the median absolute deviation, $MAD(S_{ijk})$, of the distribution of cost savings[9] for each combination:

$$\max\left(\sum_{i}\sum_{j}\sum_{k}\left(\left[(1-\beta)median(S_{ijk})-\beta MAD(S_{ijk})\right]\times z_{ijk}\right)\right),\qquad 0\leq\beta\leq 1$$

If decision makers decide to set $\beta = 0$, then the objective function solely maximises the median cost saving, ignoring any variability and therefore being risk-neutral. If $\beta = 1$, then combinations which result in low median absolute deviation are favoured. The optimal combination is captured in a binary decision variable z_{ijk}. When $z_{ijk} = 1$, it implies that combination ijk is the optimal choice. To ensure that only one combination z_{ijk} is chosen, the following constraints are required:

[9] The median and median absolute differences are chosen rather than expectation and variance as in (Tomlin, 2006) given that the cost saving for a given combination may not be normally distributed.

$$\sum_{i}\sum_{j}\sum_{k} z_{ijk} \leq 1$$

$$\sum_{i}\sum_{j}\sum_{k} z_{ijk} \geq 1$$

Since the distribution of the cost savings for each combination, S_{ijk}, is unknown because each disruption event is stochastic, a DES model was created in MATLAB R2018b SimEvents[10]. Figure 5-3 shows a screenshot of the primary elements of the model which largely map onto the processes shown in Figure 5-1 of the problem statement. Full details of the DES are reported in Appendix C.2. Each combination of ijk was simulated N times (i.e. for N replications of each combination) from which a set of cost savings for each combination could be formed $\{s_{ijk1}, \dots, s_{ijkn}, \dots, s_{ijkN}\}$, where s_{ijkn} is the cost saving for the nth replication. A detailed explanation of how s_{ijkn} is computed using the DES outputs is provided in Appendix C.3. From this, a distribution could then be formed to approximate S_{ijk}.

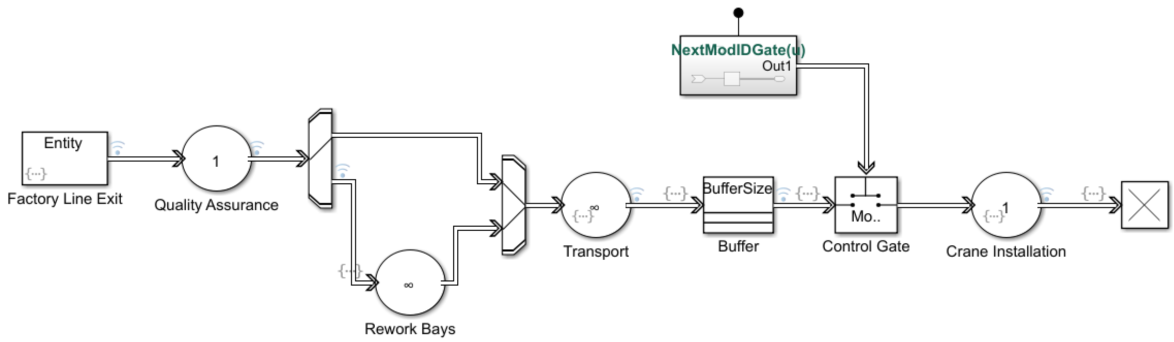

Figure 5-3: Screenshot of the primary elements of the MATLAB Discrete Event Simulation model (N.B. not all elements related to the control of the module installation are shown here).

To summarise, a two-stage SBO model composed of a DES and ILP was developed. The DES model was created to simulate the operational behaviour of a modular off-site construction system in order to output the data necessary to approximate the distribution of cost savings for each combination, S_{ijk}. These were then fed to the ILP which generated the optimal choice of disruption mitigation option combination i, on-site installation flexibility combination j, and permanent storage buffer capacity level k that resulted in the greatest cost savings according to the risk appetite of a decision maker.

[10] https://uk.mathworks.com/products/simevents/features.html

5.4.4 Validation, verification, and sample model outputs

To ensure that the results generated from this research are of use, it was critical to ensure that the model was verified and validated correctly. (Sargent, 2013) defines verification as “ensuring that the computer program of the computerised model and its implementation are correct” and validation as “substantiation that a computerised model within its domain of applicability possesses a satisfactory range of accuracy and is consistent with the intended application of the model.”

Since modular off-site construction systems enabled by on-site installation flexibility do not yet exist and are as such non-observable, this research adopted an operational verification and validation approach in which the outputs of the model were explored qualitatively and quantitatively using a choice of the methods shown in Table 5.3, as advised by (Sargent, 2013).

Table 5.3: Description and justification of validation and verification methods used in this research based on (Sargent, 2013)**. "Y" denotes where the method has been used.**

Method name	Description and justification	Conceptual Model Validation	Computerised Model Verification	Operational Validation
Animation	Visualise the positions and movements of the various entities during a simulation run to ensure that the system is behaving correctly.	-	Y	Y
Comparison to other models	Compare the results to other models that have been shown to be valid. Since this research has not been studied before, this is not possible.	-	-	-
Degenerate Test	This may be achieved by setting input parameters to values that would be expected to make the model behave in a degenerate manner. For instance, if the module output rate of the factory is high but the installation time of the crane is low, a significant number of modules should build up in the buffer.	-	Y	-
Event Validity	This may be done by observing whether behaviours in real life occur in the model. For example, running the model and observing that modules are held back for re-work when a disruption occurs.	-	-	Y
Extreme Condition Test	This may be done by setting some of the inputs to extreme and unlikely values. For instance, setting the re-work time of all modules to a very large number and observing that the total project installation time is greater than that value.	-	Y	-
Face Validity	This may be done by asking experts in the modular off-site construction industry their opinion on whether the behaviour of any of the various stages is valid.	Y	Y	Y
Sensitivity Analyses	Parameters are varied in the model to see if the changes in response are as expected.	-	Y	Y
Historical Data Validation	Given that on-site installation flexibility has yet to be enabled in real life, it is not a feasible method.	-	-	-
Internal Validity	This is done by running several replications of the model and observing if there is any significant variation in the response. If there is, then it may raise questions as to the validity of the model or whether the system under consideration can be validly modelled by the methods used.	-	Y	-
Operational Graphics	This involves displaying graphically the variation of endogenous variables over time. This may be performed for simulation-based models to see if they behave as expected.	-	Y	Y
Traces	This technique involves following the behaviour of certain entities in the model and ensuring that they are behaving as would be expected to ensure the logic of the model is correct. This could be achieved using the MATLAB Simulink Data Inspector functionality.	-	Y	Y

Following this advice, *operational graphics* were generated, and *face validity* was used by asking experts to check whether the behaviour of the model adequately reflected what they expected. Sample outputs of the application of validation and verification methods from (Sargent, 2013) are shown in the figures below.

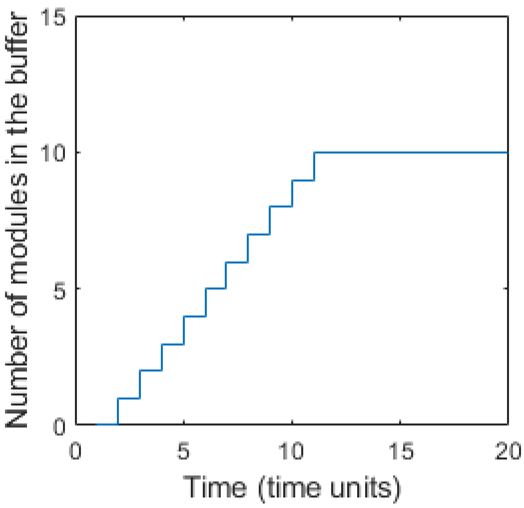

Figure 5-4: Example of a "Degenerate test" where the crane was permanently disabled which caused a build-up of modules in the buffer as they can no longer be installed.

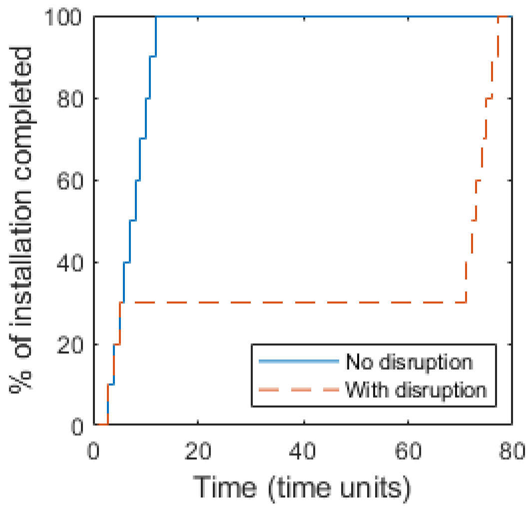

Figure 5-5: "Extreme condition test" where an abnormally long delay is triggered and system behaviour was observed to ensure that the installation completion time was correspondingly longer.

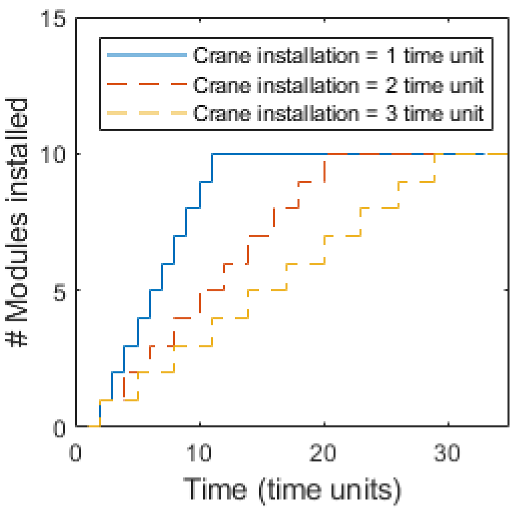

Figure 5-6: "Sensitivity analysis" to check that varying a parameter's value such as the crane installation time impacts the system as expected. In this case, the installation time of each module should increase proportionally to the crane installation time parameter.

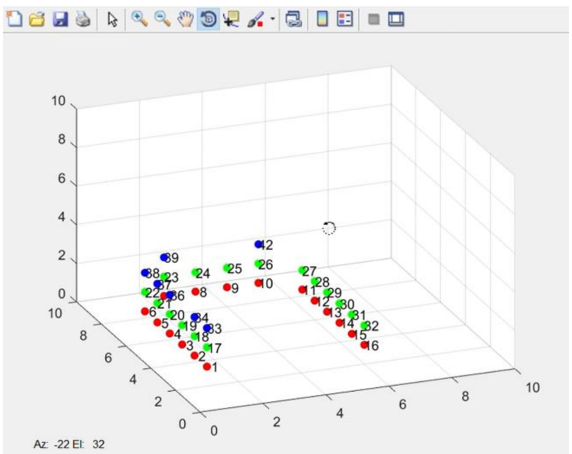

Figure 5-7: "Animation" was used to observe the behaviour of the system to ensure that modules of the correct type (each colour is a different module type) were installed in the right location in the building at the right time in accordance with the level of flexibility enabled.

5.5 Using the model to select flexibility options in a disruption management context

Inspired by (Padhi *et al.*, 2013), the above model was incorporated into an overall approach devised to aid practitioners select the most appropriate level of on-site installation flexibility compared to other investment options. The approach is comprised of fourteen steps. The suggested sequence in which they should be conducted is summarised in Figure 5-8. The steps have been partitioned into three over-arching stages: i) capturing the characteristics of the modular off-site construction system and determining the feasible investment options (including other disruption management and process improvement options as well as on-site installation flexibility), ii) determining the evaluation criteria against which the options are judged, and iii) evaluating the various options through the use of the above models.

The majority of the fourteen steps are self-explanatory but further details are given below for certain steps:

1. **Collect data on the building layout and module characteristics**: the objective of this step is first to collect an accurate depiction of the floor plan of the building so that it can be input correctly into the model. Furthermore, it is important to capture the characteristics of the modules both in terms of finish and structure of the completed building.
2. **Determine installation flexibility options that are feasible**: make use of the enablers and roadmaps for each flexibility outlined in Section 4.4 and Appendix B.4 as a starting point to discuss the feasibility of enabling each on-site installation flexibility type for the project.
3. **Determine the cost to enable feasible on-site installation flexibilities**: using the table of enablers in Table 4.4, practitioners must estimate the costs of enabling the different flexibilities individually or in various combinations with others.
5. **Collect operational data on module disruptions and the various processes**: the operational data (e.g. processing times, disruption likelihoods, and capacities) for all the different elements of the system must be gathered from the company and prepared for the DES model. There are several ways that have been commonly adopted in the past to do so (Law, 2013a). If historical data is available, then there are the options of fitting a theoretical or empirical probability distribution to the data (Law, 2013b). The former is favoured over the latter given that it can smooth out any irregularities in the data and offers the possibility that values outside of the range of the observed data, which may by chance not have occurred, can be

generated by the DES model (Law, 2013a). However, if no suitable distribution is found, then the latter is preferred. In the case where there is no data available for a given input parameter to the DES, as is often the case when evaluating new approaches, other methods have commonly been used to fill the gap. Estimating parameters by experts is one proposed solution (Reiner, 2005). Similarly, it is possible to formulate expert-based probability distributions (Firestone *et al.*, 1997; Elkjaer, 2000; Li *et al.*, 2017; Baudry, Macharis and Vallée, 2018) such as triangular probability distributions based on the lowest, highest, and most frequently estimated values of a parameter. (Ludke, Stauss and Gustafson, 1977) provide a wider range of such methods. Alternatively, finding values in literature to estimate parameters is another accepted approach (Shahtaheri *et al.*, 2017; Li *et al.*, 2018). Combinations of the above have also proved to be of use (Li *et al.*, 2018). Such approaches have been shown to be applicable to off-site construction research (Li *et al.*, 2018; Goh and Goh, 2019).

Regarding the likelihood of module disruption, practitioners are best placed to identify the disruptions that are likely to result in a module not being completed by the time it leaves the production line. The disruptions identified in Table 3.6 should be used as a starting point to guide the discussion. It may well be that two or more disruptions may result in modules not being completed (e.g. supplier delay in providing a material and damage during production). The overall effect of a module being disrupted should then be estimated to determine the likelihood a module will need re-work and the time it will take.

6. **Determine process improvement investment options and their costs**: in this step alternative investment options to improve the on-site installation phase should be discussed and costed, using for instance disruption management strategy information from Table 3.6.
8. **Determine risk aversion:** in this step decision makers must agree on a value for the measure of risk aversion, β. Any value greater than 0 would mean that the decision makers possess some degree of risk aversion. For guidance, (Tomlin, 2006; Liu and Nagurney, 2011) used a β between 0.05 and 0.25 for their mean-variance minimisation approaches.
14. **Select best combination of on-site installation flexibility and process improvement options:** In this step a sensitivity analysis to assess the effect of variations in β and how that affects the solution proposed by the simulation optimisation model must be undertaken to reassure decision makers that it is robust to their choice of β.

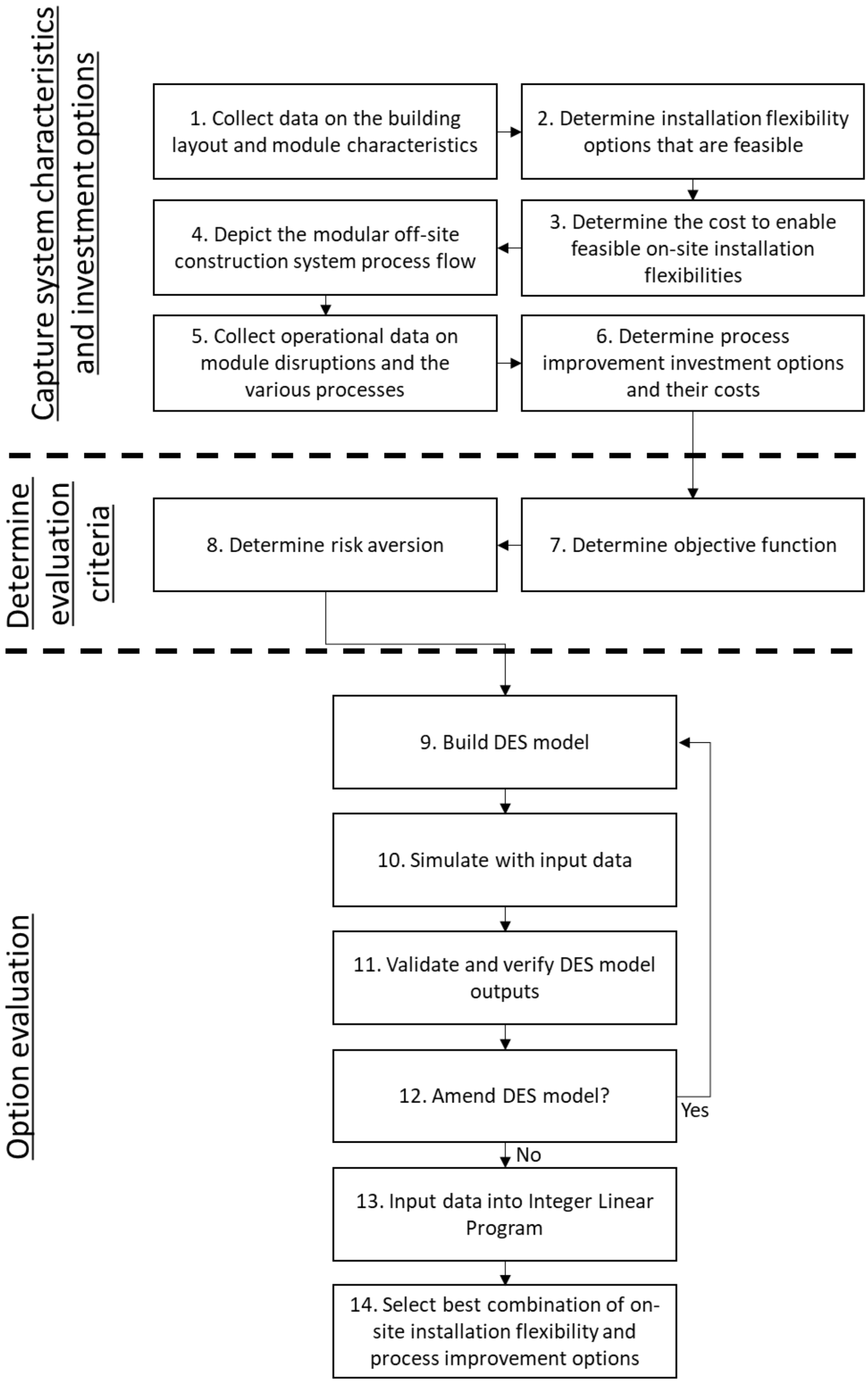

Figure 5-8: Flow chart of the various steps of the suggested approach to determining the best combination of on-site installation flexibility and other disruption management options.

In the following chapter, two case studies using the models and the approach outlined are conducted. The focus of the first case study is on understanding the behaviour of modular off-site construction systems enabled with on-site installation flexibility by using the Discrete Event Simulation model. The second case study demonstrates the use of the Simulation-Based Optimisation approach.

5.6 Summary

The first part of this chapter focussed on defining the challenge faced by decision makers when deciding on whether to invest in on-site installation flexibility given the wide range of other disruption management strategies that is also available to them. The key aspects of this problem were translated into modelling requirements against which the suitability of a range of modelling techniques was evaluated. Ultimately, a two-stage Simulation-Based Optimisation model using an Integer Linear Program and a Discrete Event Simulation model was chosen and formulated. This model was then incorporated into a decision support approach. The approach guides practitioners through the steps of identifying and evaluating the optimal combination of on-site installation flexibility and disruption mitigation improvement options that maximises cost savings while factoring in the degree of risk aversion of decision makers. The model and the approach will be applied to two case studies in the next chapter.

Chapter 6: Case studies

6.1 Introduction

Two industrial case studies are reported in this chapter. Each explored different aspects of on-site installation flexibility in a disruption management context. The first case study investigated the behaviour of on-site installation flexibility in a range of disruption conditions using the Discrete Event Simulation model developed in Chapter 5. This case study addressed Research Question 4: “How does on-site installation flexibility affect the behaviour of modular off-site construction systems?” The second case study demonstrated the approach devised in Chapter 5 to select the most effective combination of on-site installation flexibility and conventional disruption management strategies. This case contributed to addressing Research Question 3: “How can the appropriate level of on-site installation flexibility be selected to support effective disruption management?”

The objectives of this chapter are to:

1. Gain insight into the behaviour of typical modular off-site construction systems enabled by on-site installation flexibility by using the Discrete Event Simulation model in an industrial context.
2. Assess the potential value of on-site installation flexibility in combination with conventional disruption management investments by using the approach developed in Chapter 5 for selecting flexibility options in an industrial context.

Case Study A is reported in Section 6.2 followed by Case Study B in Section 6.3.

6.2 Case Study A: A high-end residential apartment block

6.2.1 Operational context

This case study was done in conjunction with a large multinational modular off-site construction company. Hence, the building in this case study is inspired from projects the company is considering undertaking and reflects many of their aspects. In this section, background information is given regarding:

- The different aspects of on-site installation flexibility to be explored.
- The building layout chosen for the case study.
- The modular off-site construction system operated by the company.

The company sought to understand two aspects of on-site installation flexibility:

1. Whether on-site installation flexibility can improve installation time of modular off-site construction systems under a range of different disruption conditions (i.e. different combinations of disruption likelihood and duration).
2. The system behaviour for different combinations of on-site installation flexibility when one or more module disruptions occur.

The building chosen for this case study was a four-storey high-end residential apartment block. The floor plan of the building was arranged around a quadrangle, as shown in Figure 6-1. The building had 16 slots per floor in each of which a single module was installed, nominally building outwards from a core. There were 4 floors and therefore 64 modules in the building. The nominal slot installation sequence was in order of increasing slot number (i.e. a module was installed in Slot 1 first, then Slot 2, etc.). The modules were produced by the factory in that same order.

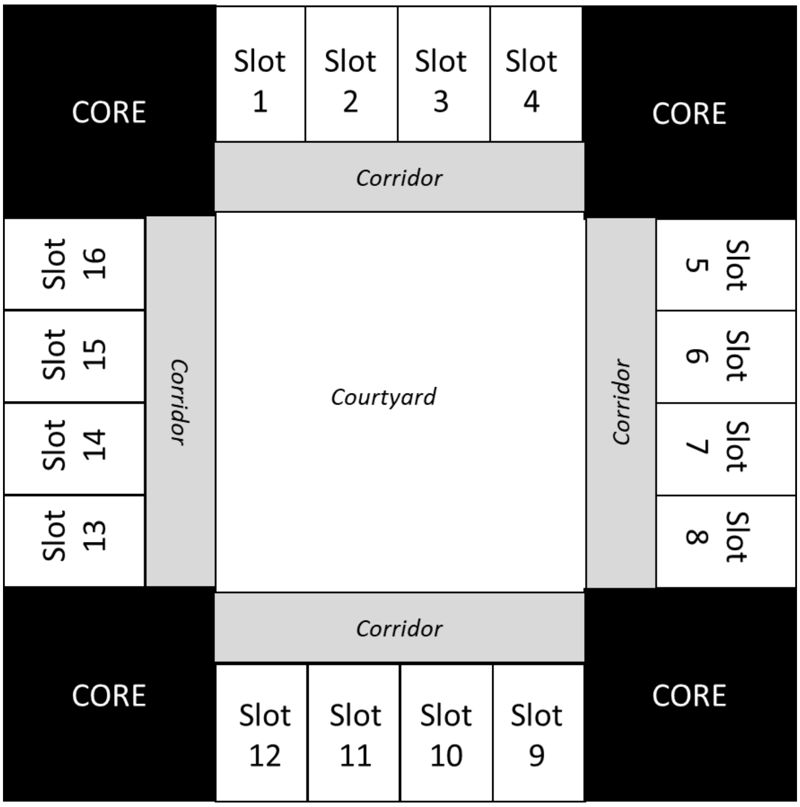

Figure 6-1: Floor plan of building (slot numbers shown are those for Floor 1).

By the time the building was completed, all modules were unique in terms of finish. This was because it was a high-end residential apartment block where customers were given the opportunity to specify the design and finish of each module (e.g. the interior fittings and colour of the walls). The company proposed several different levels of lateral assignment flexibility. This entailed that some of the work that differentiated the modules was postponed to the site (e.g. painting the walls at the site rather than at the factory). The company suggested that five different levels of similarity of modules should be tested: from 1 module type per floor (i.e. all identical in terms of finish similarity when they are delivered to the site) to 2, 4, 8, and 16 per floor (i.e. all 16 are unique in terms of finish similarity when they are delivered to the site). A system operating with fewer than 16 module types per floor was considered to have lateral assignment flexibility enabled. The floorplans for the different levels are depicted in Figure 6-2.

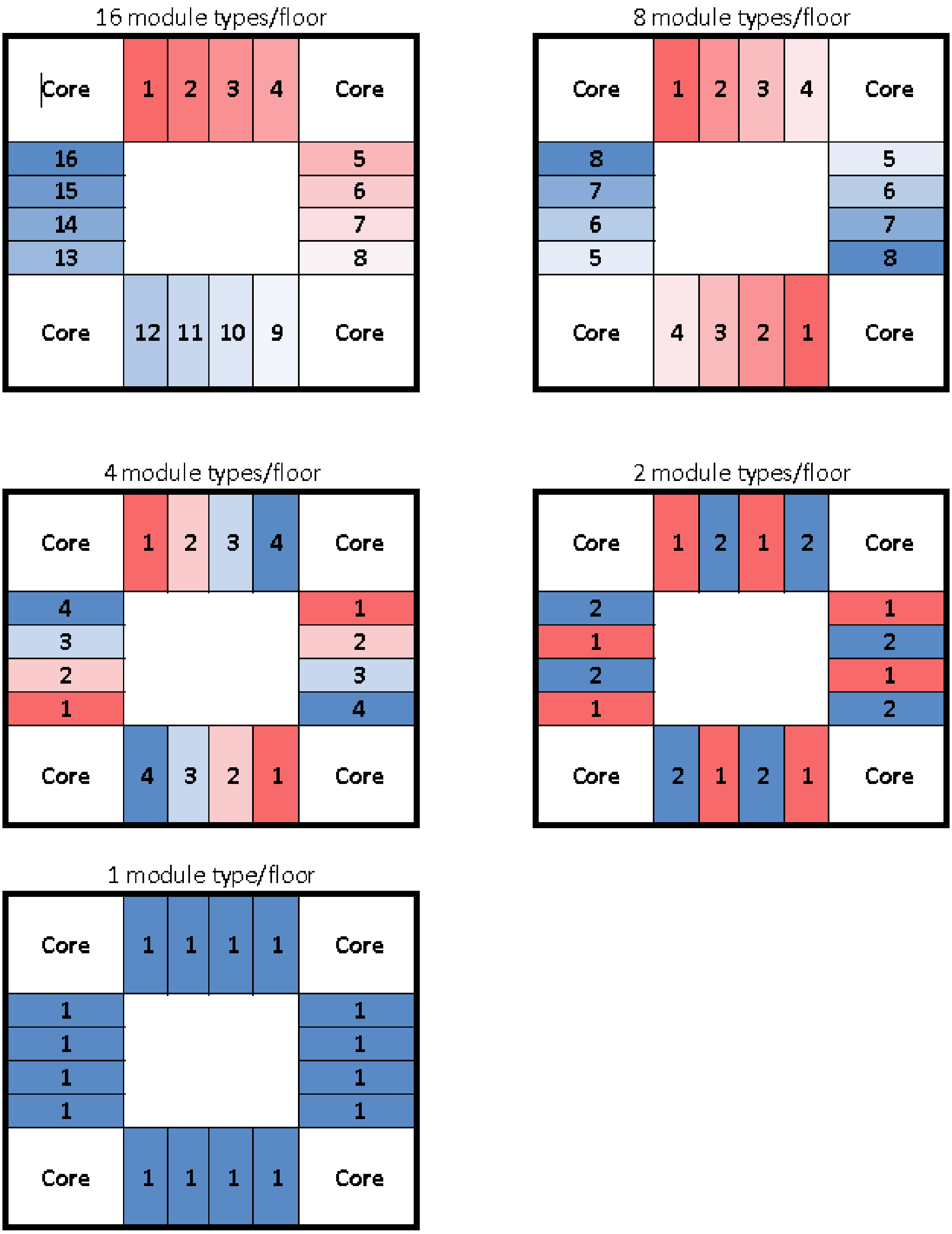

Figure 6-2: Floor plans for various numbers of module types per floor. Numbers in the slots correspond to module types.

The company sought to run a system with just in time delivery of the modules to the site. The modular off-site construction system that the company operated is presented in Figure 6-3.

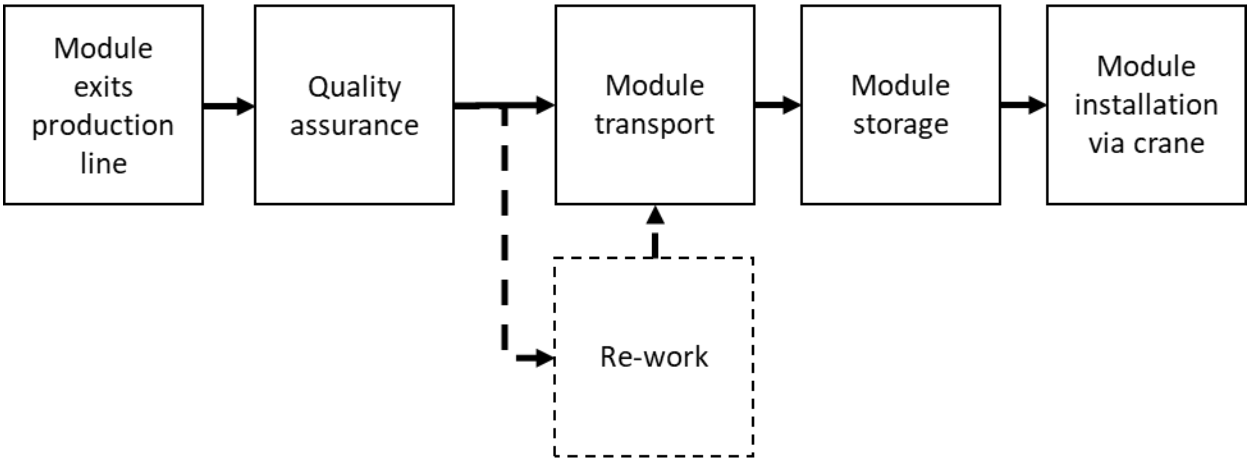

Figure 6-3: Flow chart of the modular off-site construction system of Case Study A.

The elements in the system have been organised so that they operate in takt. The operating parameters were adjusted in order not to reveal sensitive company information and are shown in Table 6.1. When a module exits the factory production line, it goes through quality assurance that checks for any defects or uncompleted work as a result of Type 1 disruptions inbound to and at the factory (see Figure 4-1). A module is sent for re-work for a certain duration should it fail the quality assurance (this is referred to as the disruption duration). As such, from the point of view of the on-site installation operations, this means that each module has a probability of being disrupted. If no disruptions occur, the system is expected to complete its installation phase (the duration from when the first module leaves the factory production line to the time all modules have been installed) in 66 time units. This is equal to the sum of the installation time of all the modules plus the start-up quality assurance time and transport time.

Table 6.1: Operating parameters for Case Study A.

Parameter	Value
Crane installation time per module	1 time unit
Factory module production rate	1 time unit/module
Transport time from factory to buffer	1 time unit
Quality assurance process	1 time unit
Buffer capacity	Unlimited
Number of slots per floor, N_{sf}	16
Number of slots in building, N_{sb}	64
Number of floors	4

6.2.2 Experimental design

Representatives from the company said that variation in transport time, quality assurance duration, and crane installation time were not areas of concern and as such could be treated as constants using representative values. In this way, the variation in the performance metrics in Table 6.2 could more easily be attributed to the parameters in Table 6.3 that were varied.

To investigate the two aspects of interest to the company (see Section 6.2.1), two full factorial experimental designs were devised:

Experimental Design 1: The purpose of this set of experiments was to investigate the first aspect of interest to the company: whether on-site installation flexibility can improve installation time of modular off-site construction systems under a range of combinations of disruption probability and duration. Each module was assumed to have an equal probability of disruption for a given combination of parameters. The insight from this set of experiments is useful to practitioners as it shows the overall performance of the system (including projects with no disruptions) that can be expected by implementing on-site installation flexibility.

Experimental Design 2: This set of experiments explored the second aspect of interest to the company: the behaviour of the system for different combinations of on-site installation flexibility when one or more module disruptions occurred. The insight from this set of experiments is useful to practitioners as it shows the response of the system to a known number of disruptions for each combination of on-site installation flexibilities. Hence, unlike the first set, the behaviour of the system was not obscured by cases where no disruptions occurred, particularly at low module disruption probabilities. Therefore, practitioners can better understand how the system behaves for different flexibility combinations when a disruption occurs.

The behaviour of the system was measured against six performance metrics (sometimes referred to as dependent variables) of interest to the company. These dependent variables are listed in Table 6.2 for each experimental design. Both full factorial experimental designs included 40 different combinations of on-site installation flexibility (the product of 2 vertical sequence, 2 lateral sequence, 2 vertical assignment, and 5 lateral assignment levels). Experimental Design 1 combined these with 66 combinations of disruption probability and duration. Experimental Design 2 combined these with 54 combinations of the number of modules disrupted and their duration. The independent variables (also referred to as factors) are shown in Table 6.3.

Table 6.2: Dependent variables for which the conditions for an ANOVA were assessed for each of the experimental designs: 1) where *module disruption probability* was a factor, and 2) where *number of modules disrupted* was a factor. Y = Yes.

Dependent variable	Experimental Design 1	Experimental Design 2
Reduction in installation time	Y	-
Total reduction in the floor completion time	-	Y
Percentage reduction in delay	-	Y
Percentage reduction in the module dwell time in the buffer	-	Y
Percentage reduction in the maximum number of modules in the buffer	-	Y
Percentage of modules that changed position from the nominal module installation sequence	-	Y
Percentage of slots that changed position from the nominal slot installation sequence	-	Y

Table 6.3: Range of independent variables for which the modular off-site construction system was tested.

Independent variable (factor)	Levels
Vertical assignment flexibility	Yes/No
Lateral assignment flexibility	16 (i.e. no lateral assignment flexibility), 8, 4, 2, 1 module types/floor
Vertical sequence flexibility	Yes/No
Lateral sequence flexibility	Yes/No
Duration of disruption (time units)	1, 4, 8, 12, 16, 20
Module disruption probability *(Experimental Design 1 only)*	0.01, 0.02, 0.04, 0.06, 0.08, 0.1, 0.12, 0.14, 0.16, 0.18, 0.2
Number of modules disrupted *(Experimental Design 2 only)*	1, 2, 4, 6, 8, 10, 12, 14, 16

For the purposes of this case study, the Discrete Event Simulation model detailed in Section 5.4.3 was used. There was no need to make use of the remainder of the SBO model described in Section 5.4 given that the company was solely interested in learning more about the behaviour of the system.

(Banks and Nelson, 2014) state that the following equation can be used to determine the minimum number of replications R required to reach a given confidence level α and precision ϵ (e.g. being within ±1% reduction in the delay)[11]:

[11] The equation is valid when R is at least 50, which is the case here.

$$R \geq \left(\frac{z_{\frac{\alpha}{2}} \times S_0}{\epsilon}\right)^2$$

$z_{\frac{\alpha}{2}}$ is the z-score corresponding to the $100(1-\frac{\alpha}{2})$ percentage point of the standard normal distribution. S_0 is the estimate of the population variance obtained from an initial number of simulation replications. To obtain a good estimate for S_0, it is necessary firstly to run a number of replications beyond which there would be little further change in S_0 (Ritter *et al.*, 2011). This number was determined by plotting the mean and standard deviation for each dependent variable at all combinations of input variables for between 1 and 50 replications. Example plots are shown in Figure 6-4 and Figure 6-5.

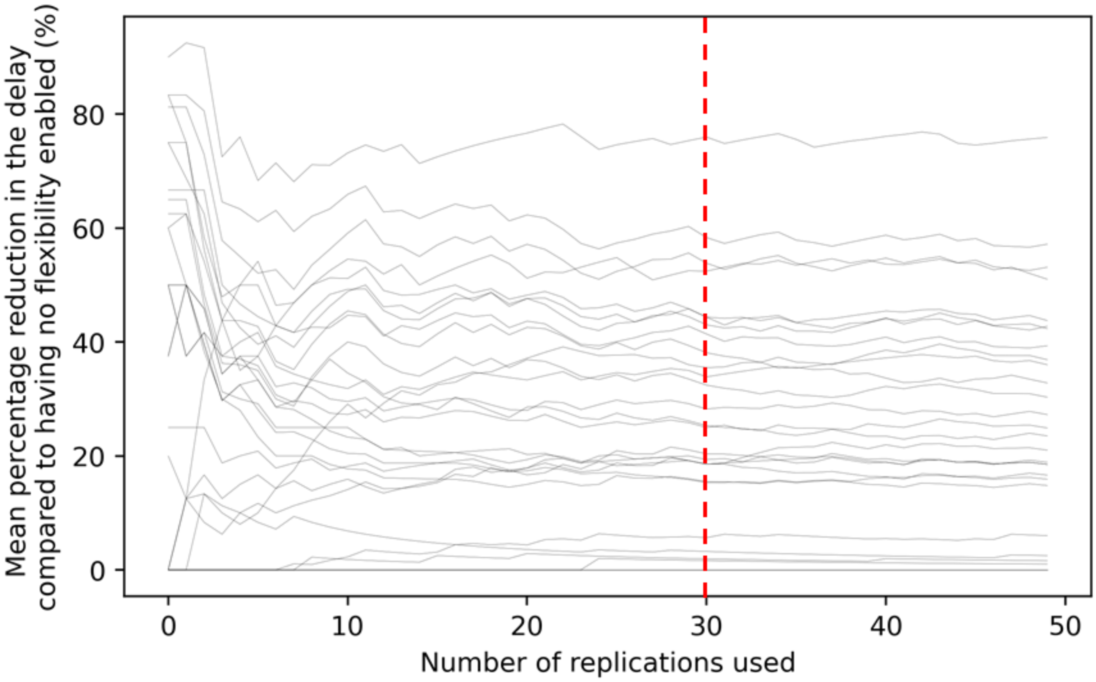

Figure 6-4: Effect of number of replications on the mean percentage reduction in delay. Not all combinations are shown for legibility purposes.

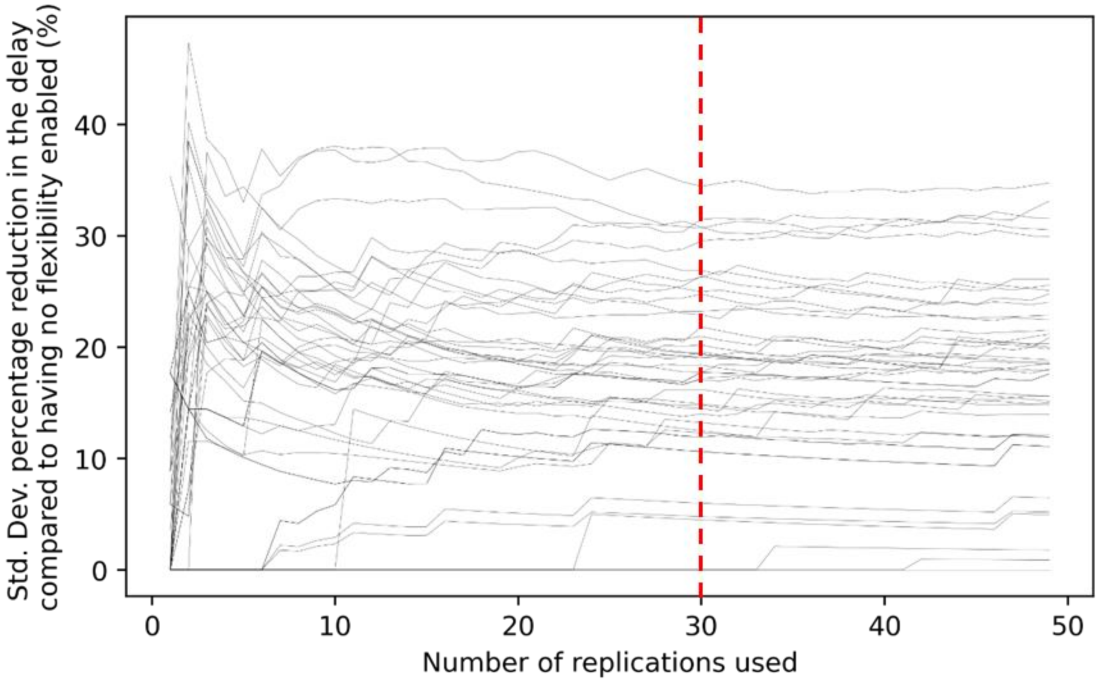

Figure 6-5: Effect of number of replications on the standard deviation of the percentage reduction in delay. Not all combinations are shown for legibility purposes.

After about 30 replications, the mean and standard deviation of the dependent variables were found to stabilise. For good measure, 50 was chosen as the initial number of replications based on which S_0 could be obtained. However, the equation assumes that the data from the replications is normally distributed. To verify this, histograms of the dependent variables were generated (e.g. Figure 6-8 and Figure 6-9). It was evident from the histograms that the above equation could not be used to determine the minimum number of replications given the non-normality of the distributions.

Given that there is little change in the mean of the dependent variables beyond 30 replications as well as the fact that each replication is time consuming to run, 50 replications were deemed to be sufficient to obtain a good representation of the system behaviour. Similar DES studies used between 10 and 100 replications (Padhi *et al.*, 2013; Vidalakis, Tookey and Sommerville, 2013; Arashpour *et al.*, 2015; Goh and Goh, 2019). In all, 132,000 and 108,000 simulations were performed for experimental designs 1 and 2 respectively.

6.2.3 Overview of simulation outputs

The purpose of this section is to give an overview of the types of outputs that were obtained from the simulation model. First, typical results for individual replications are presented after which example outputs combining all 50 replications of a given experimental design point (i.e. a given combination of parameters from Table 6.3) are shown.

To this end, consider the results of the following combination of parameters from Experimental Design 2[12]:

- Vertical and lateral assignment flexibilities are enabled, where there are 2 unique module types per floor, in addition to lateral sequence flexibility.
- 4 out of 64 modules are delayed for 12 time units.

Figure 6-6 and Figure 6-7 show results for a typical replication, in this case number 43 out of 50. Figure 6-6 shows that enabling flexibility allowed the installation to be completed 8 time units earlier than the same disruption scenario without flexibility. When the first disruption occurred, the installation resumed earlier than in the case without flexibility enabled. This is indicated by the blue line plateauing for 13 time units (i.e. the 1 time unit transport time plus the 12 time unit disruption) before installation resumed. Figure 6-7 shows that in the case without flexibility, the buffer filled up with three times as many modules at its peak than when flexibility was enabled. This is because when a disruption occurs, all subsequent modules cannot be installed and are stored until the disrupted module arrives from re-work. However, when flexibility is enabled, the installation process can resume earlier, resulting in a much lower build-up of modules. The number of modules in the buffer can vary over time for several reasons. For instance, when a re-worked module arrives at the same time as an undisrupted module, the number of modules in the buffer increases because the crane may only install one module at a time. Moreover, when a module fails quality assurance and goes to re-work, the number of modules in the buffer in the next time period will be one lower than it would otherwise have been. Furthermore, should no module suitable for installation be available in the buffer, the number of modules will remain the same or increase.

[12] Note that comparable outputs were obtained for Experimental Design 1.

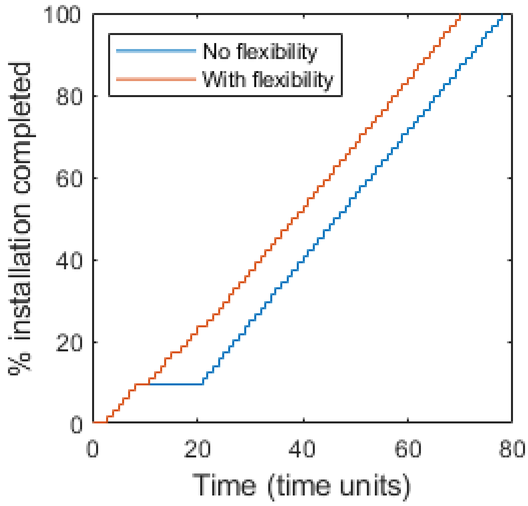

Figure 6-6: Percent of installation completed over time.

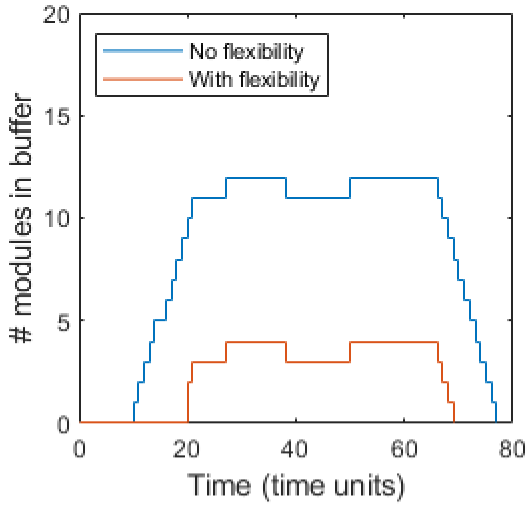

Figure 6-7: Number of modules in the buffer over time.

Figure 6-8 and Figure 6-9 are histograms of two of the dependent variables from Table 6.2. These were created using outputs from all 50 replications for the same experimental design point as defined above. A variation in the reduction in installation delay and the maximum number of modules in the buffer can be observed. This is because the behaviour of the system depends on which 4 out of the 64 modules are disrupted.

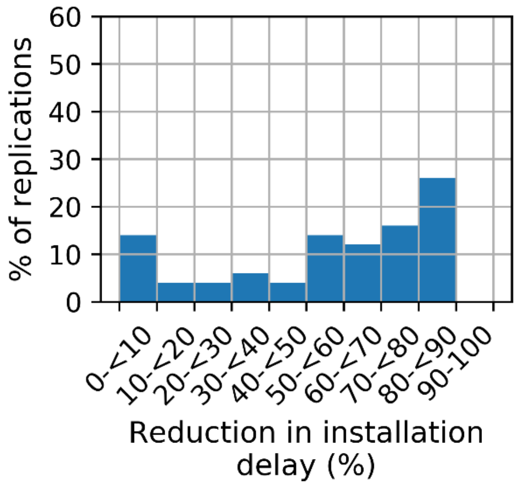

Figure 6-8: Percentage of replications that resulted in a given reduction in installation delay when flexibility is enabled.

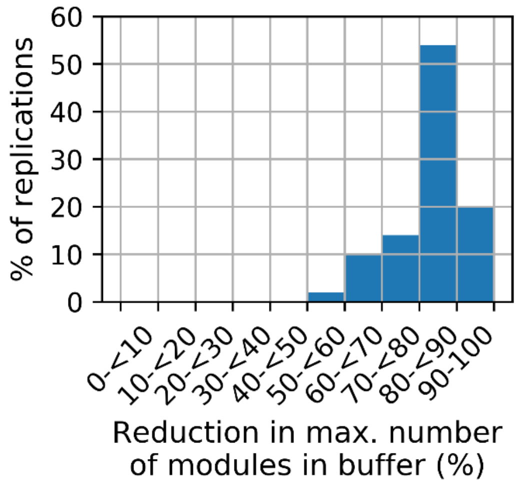

Figure 6-9: Percentage of replications that resulted in a given reduction in the maximum number of modules in the buffer when flexibility is enabled.

6.2.4 Preliminary exploratory analysis of the simulation outputs

A range of different statistical techniques may be used to analyse the results from the simulation model. However, the data must conform to the assumptions applying to those techniques. Otherwise, they may not be used as they may lead to false conclusions (Montgomery, 2008). As such, a preliminary analysis of the data was conducted with the aim of identifying a suitable statistical technique.

An ANOVA can be used to investigate the main and interaction effects that factors have on a dependent variable (Montgomery, 2008). In other words, an ANOVA would allow one to see which factors influence the system's behaviour (e.g. does enabling vertical installation flexibility reduce the delay compared to not having it enabled) and whether or not certain factors interact together to improve or reduce performance (e.g. does enabling both lateral and vertical installation sequence flexibility reduce the delay more than each would separately). The data was assessed to verify whether it fulfilled the required conditions for an ANOVA for various dependent variables of interest for each of the two experimental designs, as shown in Table 6.2. The dependent variables were used to compare the differences (percentage or absolute) with and without flexibility enabled. For Experimental Design 1, percentage differences could not be used given that in replications where no disruption occurred, the calculation would result in a division by 0. Hence absolute differences were considered instead.

One of the necessary conditions to conduct an ANOVA is that there is an equal variance in the dependent variable for each combination of factor levels (Montgomery, 2008). To verify this, a Levene's test for homogeneity of variance was conducted. The null hypothesis of homogeneity of variance across the different combinations of factors was rejected at an $\alpha = 0.05$ (95% level of confidence) for all dependent variables. Following the advice from (Montgomery, 2008), various variance-stabilising transformations of the dependent variables were conducted using the Box–Cox procedure (Box and Cox, 1982) in the hope that the transformed data would meet the assumption. However, the null hypothesis of homogeneity of variance across the different combinations of factors was rejected again for an $\alpha = 0.05$ for all dependent variables as they all had a p-value of near 0. Consequently, an ANOVA could not be used for either experimental design.

Alternative tests were considered based on the advice from (Osborne and Sheng, 2011), including the Welch t-test for unequal variances (Welch, 1947) and the Mann-Whitney U test (Whitney, 1947) in conjunction with a Brown-Forsythe Test (Brown and Forsythe, 1974) for pair-wise comparisons of means and medians respectively. The Welch t-test was found not to be suitable given that the dependent variables were often skewed and therefore would lead to erroneous conclusions (Osborne and Sheng, 2011). Nor could the Mann-Whitney U test be used to conclude a difference in the medians of the dependent variables given that the Brown-Forsythe Test also showed differences in variance.

Nevertheless, it was evident by inspecting the data that a difference could be observed between different combinations of factor levels. Given the lack of adequate statistical tests for the data obtained through the simulation, the remainder of the analysis and insights drawn from this case study are therefore given in graphical form. Even though the findings described next are specific to this case, they illustrate the behaviour of a typical modular off-site construction system from which valuable insight can be drawn.

Figure 6-10 shows how the analysis of the output of the simulation model was structured. The analysis was divided into two parts. The first focussed on the primary metrics of interest to practitioners: the installation time and the delay reduction. For this, an analysis of the baseline performance of the system without any flexibility for different disruption conditions was conducted. Next, the behaviour of the system for each on-site installation flexibility was analysed under a range of different disruption conditions. The performances of different combinations of flexibilities were then compared in terms of delay reduction. The second part of the analysis focussed on comparing the behaviour of the system under different flexibility combinations for other metrics of importance to practitioners such as the maximum number of modules in the buffer.

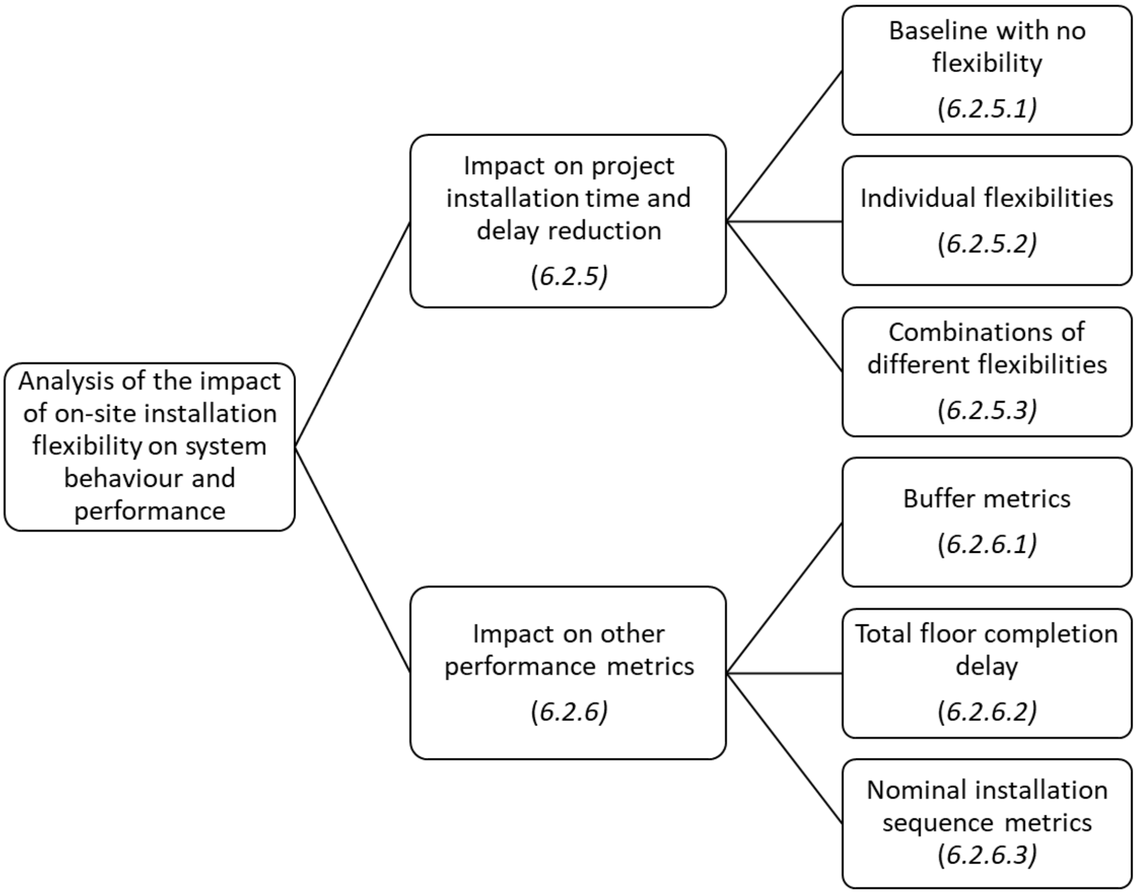

Figure 6-10: Structure of the analysis of the outputs of the discrete event simulation.

6.2.5 Impact of on-site installation flexibility on project installation time and delay reduction

6.2.5.1 *Baseline analysis: no on-site installation flexibility enabled*

Figure 6-11 shows the mean installation delay of the system at different levels of module disruption probabilities and durations. At disruption probabilities below approximately 0.06, i.e. line A on Figure 6-11, the mean installation delay increased with disruption probability and duration. The greater the probability that a module was disrupted, the greater the chance that one of the 50 simulation replications experienced a disruption and hence the greater the mean installation delay. The curvature in the gradient below line A can be explained by the fact that the relative increase in mean delay with disruption duration was greater than the relative increase with disruption probability. Indeed, an increase in disruption duration of X time units resulted in a linear increase in mean installation delay of X time units whereas the relative increase in mean delay with disruption probability was less pronounced and diminished as the probability approached the value of 0.06 (line A).

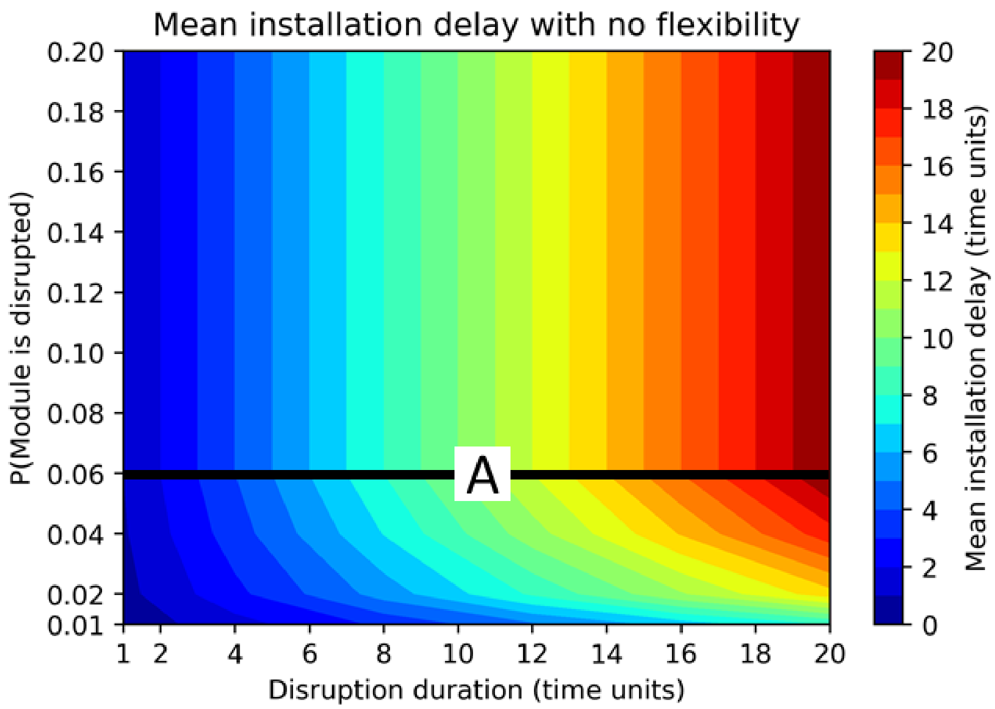

Figure 6-11: Mean installation delay of the system when no flexibility is enabled.

***<u>Proposition</u>:** Without on-site installation flexibility, if it is unlikely for a module to be disrupted during a project (i.e. it is feasible to reduce the probability a module is disrupted below a threshold probability), reducing both disruption duration and the probability a module is disrupted can reduce the mean installation time in the few cases where a disruption will occur.*

When the disruption probability exceeded approximately 0.06 (i.e. the region above line A), the delay experienced by the system became independent of the probability that a module is disrupted. This is best explained through the following hypothetical example where any module disruption lasts eight time units and the buffer is large enough to store modules for the longest foreseeable disruption. Say the first module to be produced is found to require re-work. During this time, the factory will release eight new modules that must be held in the buffer (as flexibility is not enabled). Once the disrupted module has been fixed, it is sent to the site and installed, allowing the modules that were waiting in the buffer then to be installed one by one. Because the system operates on a just-in-time delivery from the factory, when a new module arrives in the buffer, another is installed on site resulting in a net zero change of the number of modules in the buffer. Consequently, the buffer in effect forms a safety stock of eight modules until the factory has produced all the modules required of it – at which point the buffer begins to deplete. Thus, if another module is disrupted, the impact of its eight time unit disruption will not be experienced by the system since the buffer still holds eight other modules pending to be installed. In short, when one module has already been disrupted, any disruptions of equal or shorter length to subsequent modules will not prolong the overall installation delay any further.

***<u>Proposition</u>:** Without on-site installation flexibility, if a disruption is inevitable (i.e. it is not feasible to reduce the likelihood of a module being disrupted below a level where a disruption during a project is not expected), decision makers should focus on reducing the duration of the disruption rather than the probability.*

It is possible to estimate analytically the probability $P(Module\ is\ disrupted)$ corresponding to line A in Figure 6-11. If this module disruption probability value is exceeded, at least one module is almost certain to be disrupted.

The probability that no modules are disrupted during a project is given by:

$$P(No\ modules\ disrupted) = 1 - P(At\ least\ 1\ module\ disrupted) \qquad (1)$$

It may also be expressed as follows:

$$P(No\ modules\ disrupted) = [1 - P(Module\ is\ disrupted)]^{N_m} \quad (2)$$

where N_m is the number of modules in the project. Setting Equation (1) equal to Equation (2) and re-arranging:

$$P(Module\ is\ disrupted) = 1 - \sqrt[N_m]{1 - P(At\ least\ 1\ module\ disrupted)} \quad (3)$$

Let $P(At\ least\ 1\ module\ disrupted) = 0.99$ to find the value of $P(Module\ is\ disrupted)$ that would likely result in at least one module being disrupted during a project of size N_m. Consider a project of size $N_m = 64$ modules, as was the case in Figure 6-11. Equation (3) yields $P(Module\ is\ disrupted) = 0.07$, which is very close to that shown in Figure 6-11 (which lies between the module disruption probability steps 0.06 and 0.08 that were simulated).

Figure 6-12 shows the value of $P(Module\ is\ disrupted)$ at which there is a 99% chance of at least one module disruption occurring for different project sizes. If there are fewer modules in a project, there are fewer occasions for a module to be disrupted. Consequently, for a small project, the probability individual modules are disrupted must be higher if there is a 99% chance of at least one module being disrupted. Hence, line A would correspond to a higher value of $P(Module\ is\ disrupted)$.

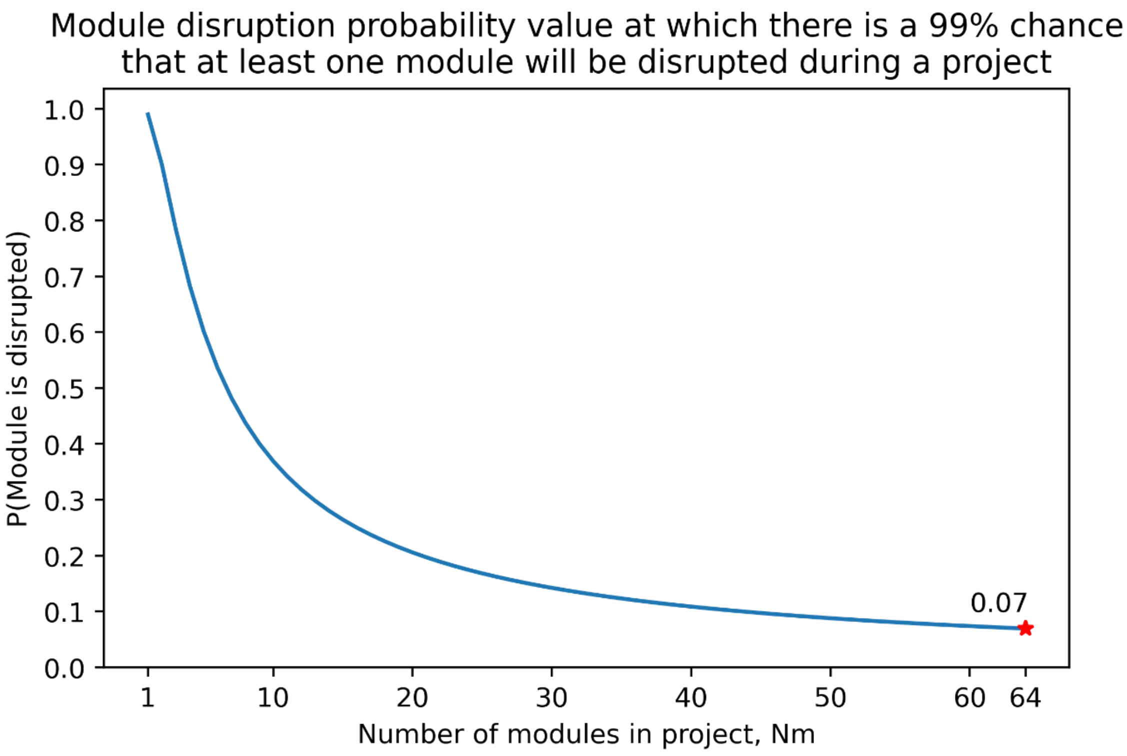

Figure 6-12: Module disruption probability at which there is a 99% chance that at least one module will be disrupted.

6.2.5.2 *Impact of each individual type of on-site installation flexibility*

Insight into the ability of each of the four on-site installation flexibility types to mitigate installation delay was gained by analysing the behaviour of each under different disruption conditions.

Impact of vertical assignment flexibility: Figure 6-13 shows that vertical assignment flexibility only becomes beneficial when the disruption duration exceeds 16 time units, the time to deliver all the modules for each floor. The explanation for this is that should a module be disrupted, it takes 16 time units to deliver another module of identical type if vertical assignment flexibility is the only installation flexibility to be enabled. Hence, at any disruption duration shorter than 16 time units, the issue with the disrupted module would have been resolved before the next module of the same type arrives at the site. Therefore, the mean percentage reduction is 0 for disruption durations shorter than 16 time units in this case.

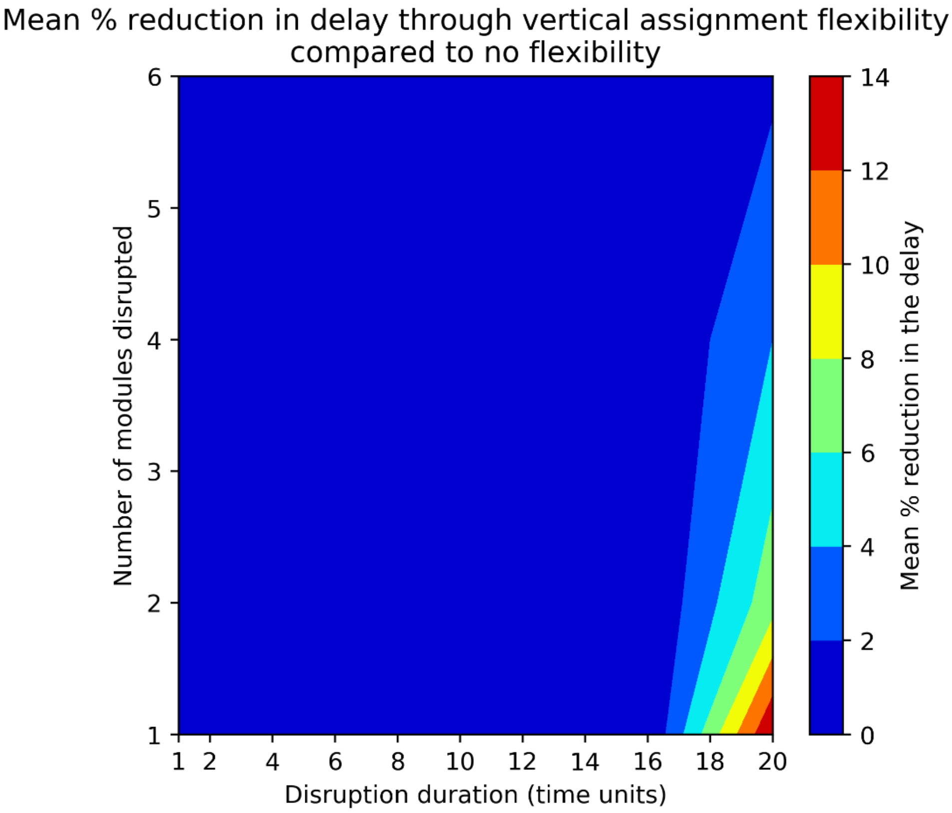

Figure 6-13: Mean percentage reduction in delay achieved through enabling vertical assignment flexibility compared to not having any flexibility enabled.

For disruption durations above 16 time units, as the probability of disruption increased, the mean percentage reduction in the delay decreased. This is because vertical assignment flexibility relies on there being modules from an upper floor to be re-assigned to a slot on a lower floor. When the number of disrupted modules increased, there was a higher chance that a disrupted module was destined for a slot on the top floor for which vertical re-assignment from a higher floor is not possible.

<u>Proposition</u>: *Vertical assignment flexibility is useful in conditions where the disruption duration of a module is longer than the time it takes for a module of an identical type to be delivered to the site.*

Impact of vertical sequence flexibility: Figure 6-14 reveals that disruption duration had a strong influence on the mean percentage reduction in the delay.

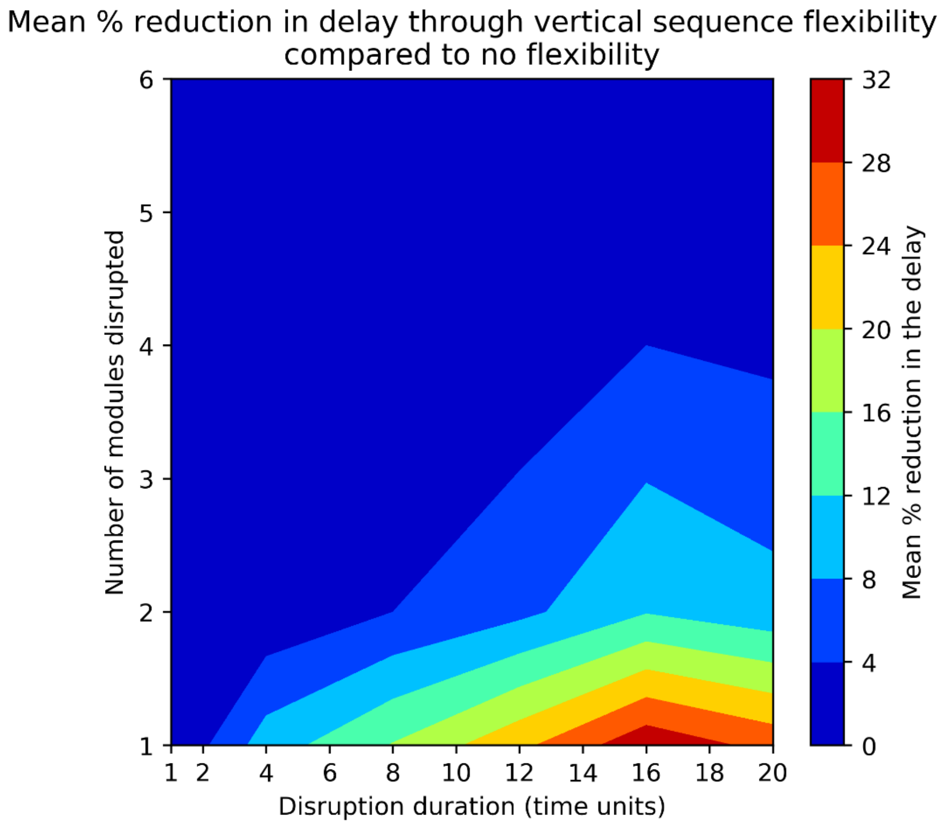

Figure 6-14: Mean percentage reduction in delay achieved through enabling vertical sequence flexibility compared to not having any flexibility enabled.

For disruption durations below the 16 time units it took to install a complete floor, the mean percentage reduction in delay increased with disruption duration. This is because for shorter durations, it was more likely that a disrupted module was remedied before installation could commence on the floor above through vertical sequence flexibility. At disruption durations above 16 time units, the benefit of vertical sequence flexibility diminished with increasing disruption duration. This is because if a disruption lasted more than 16 time units, modules could only be installed on the upper floor up to the slot directly above the empty slot on the floor below. The peak reduction in delay therefore occurs exactly at 16 time units. If each floor were to have, say 20 modules per floor, then the peak would be expected to occur at a disruption duration of 20 time units. Vertical sequence flexibility is most effective therefore for systems where the installation time per floor is comparable to the expected disruption duration.

Proposition: *Vertical sequence flexibility is most effective where the installation time per floor is comparable to the expected disruption duration.*

As the number of modules that were disrupted increased, the effectiveness of vertical sequence flexibility decreased, as seen on Figure 6-14. Again, if there are more modules being disrupted, there is a greater chance that at least one of them was bound for a slot on the top floor of the building. Consequently, the ability to continue installing modules on a higher floor is of no use given that there is none. Therefore, as the number of modules being disrupted increased, the mean percentage reduction decreased. As such, vertical sequence flexibility would be most effective for buildings that have multiple floors.

Proposition: *Vertical sequence flexibility is more effective at reducing delays in multi-storey building projects.*

Management should therefore ensure that modules destined for the top floor have a low probability of disruption. This could be achieved through several ways. For example, ensuring that parts for these modules are delivered ahead of time or assigning the most skilled workers to these modules to reduce error rates.

Proposition*: To reduce delay, management should invest in ensuring that the modules that are nominally intended for the top floor be produced with minimal probability of disruption.*

Impact of lateral sequence flexibility: When the disruption duration was 1 time unit, disrupted modules arrived from the re-work at the same time as the next module and as such lateral sequence flexibility gave no benefit. Hence the resulting project delay was always 1 time unit.

Figure 6-15 shows that at lower values of disruption duration, lateral sequence flexibility gave a greater benefit in terms of the mean percentage reduction in the delay compared to no flexibility. To explain this, consider Table 6.4 that reports the project delays for a range of module disruption scenarios for a given floor. For instance, should the module assigned to Slot 14 be disrupted for a duration of 4 time units, the resulting project delay would be 2 time units.

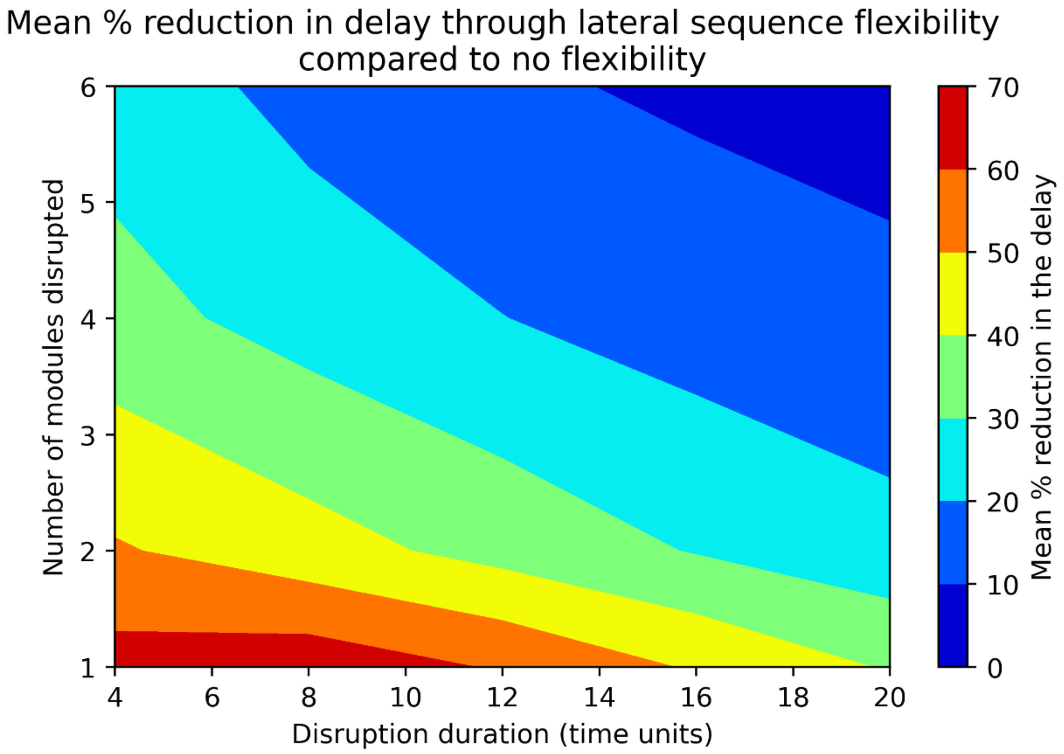

Figure 6-15: Mean percentage reduction in delay achieved through enabling lateral sequence flexibility compared to not having any flexibility enabled.

When a disruption occurs, it will always result in a delay of at least 1 time unit (corresponding to the time it takes for the next module to arrive). Lateral sequence flexibility allows the system to continue installing other modules as soon as they arrive while the disrupted module is being remedied. As a result, if the installation of the floor is still in progress when the disrupted module arrives, the delay is limited to 1 time unit – as in the scenarios shaded in white. The longer a module is disrupted, the more likely that the rest of the modules on the floor will be installed before it arrives. Consequently, the installation must pause, resulting in a delay greater than 1 time unit – as in the scenarios shaded in orange. What is more, Table 6.4 shows that when the disruption duration is 4 time units, there are two more orange scenarios than for a 2 time unit disruption. The closer the affected slot is to the end of the floor, the shorter the time required to install the rest of the modules on the floor compared to the disruption duration. Hence, the installation must pause for longer, thereby increasing the delay. Lateral sequence flexibility is therefore a good choice for buildings with a high ratio of time to complete the installation of a floor to disruption duration.

Table 6.4: Delay in time units when the module assigned to the nth slot on a floor is disrupted.

Slot for which module is disrupted:		12	13	14	15	16
Delay for disruption duration of…	**… 2 time units:**	1	1	1	1	2
	… 4 time units:	1	1	2	3	4

The greater the number of disrupted modules, the higher the chance an orange scenario will occur. As such, lateral sequence flexibility is more effective when it is less likely that a module is disrupted.

Proposition: *Lateral sequence flexibility is a good choice when the installation time per floor is large compared to the disruption duration of modules.*

Management should reduce the disruption duration of modules that are intended for slots towards the end of a floor. There are several ways in which this could be achieved. For instance, holding a safety stock of parts that are most likely to break for those modules, having the option to expedite the delivery of parts, or improving the effectiveness of labour assigned to doing repairs.

Proposition: *To reduce delay, management should invest in ensuring that the modules that are nominally intended for slots later in a floor's installation sequence be produced with minimal disruption duration.*

Impact of lateral assignment flexibility: Figure 6-16 shows that as the number of modules of a given type per floor increased, the mean percentage reduction in delay increased. This is because if there are more modules of a given type on a floor, it is more likely that a module of the same type as a disrupted module can be re-assigned to the disrupted module's slot. If there are fewer modules of a given type, then it is more likely that the last module of a given type to be installed on a floor is disrupted. In this case, lateral assignment flexibility would no longer be of use as there would be no further modules of the same type to be re-assigned to the disrupted module's slot.

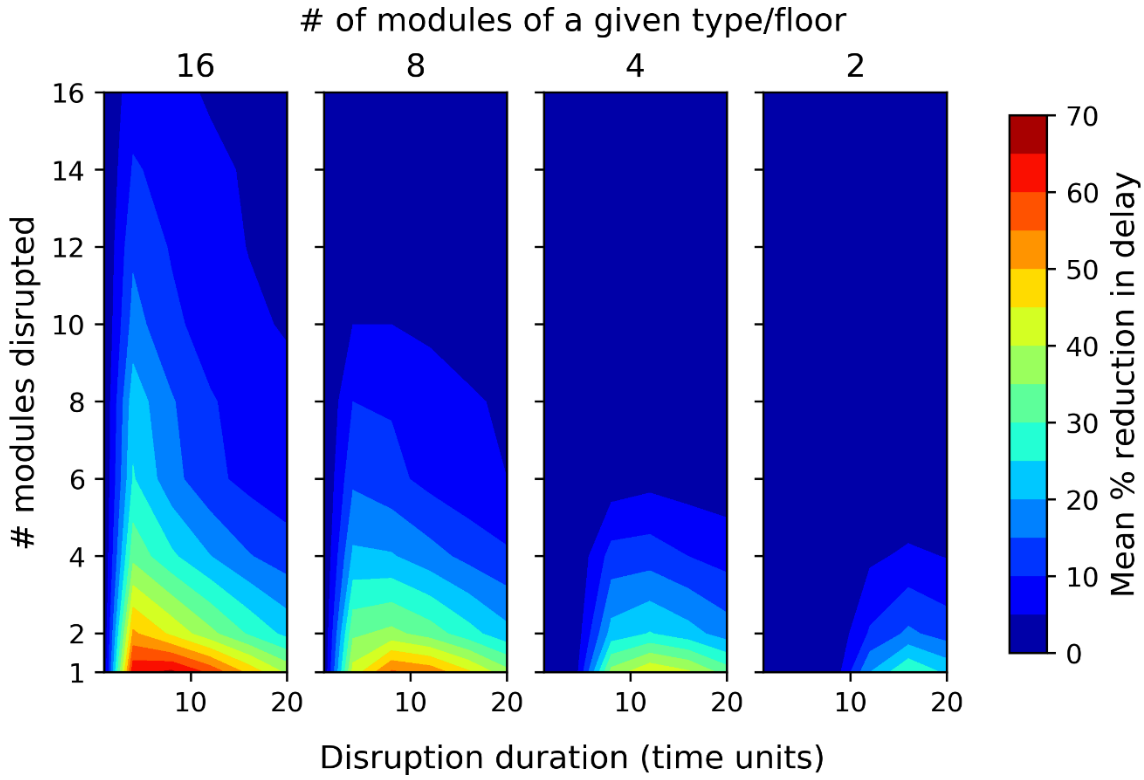

Figure 6-16: Mean percentage reduction in delay through enabling lateral assignment flexibility compared to no flexibility for various numbers of modules of a given type per floor.

Figure 6-16 also shows that the mean percentage reduction in delay appears to reach a maximum at a certain disruption duration across all four graphs. For instance, in the case where there were four modules of identical type per floor, a peak in mean percentage reduction occurred at approximately 12 time units. Below this value, the percentage reduction tapered off. This is because as the disruption duration approached the time it took for another module of identical type to be delivered to the site, the benefit of being able to install the new module reduced as the disrupted one would have anyway been delivered shortly after the other one arrived. When the disruption duration was less than or equal to the time it took for another module of identical type to be delivered to the site, no reduction in delay could be achieved through lateral assignment flexibility. Above 12 time units, the mean percentage reduction in delay reduced as there was a greater chance that the disrupted module had not been repaired by the time the installation progressed to the last slot requiring that type of module, after which the installation had to halt.

Proposition*: The performance of lateral assignment flexibility improves as the number of modules of the same type on a given floor increases.*

Lateral assignment flexibility and lateral sequence flexibility have the same effect on the reduction of the delay when all modules on a floor are identical (i.e. one module type per floor which corresponds to 16 modules of a given type per floor). Enabling lateral installation sequence flexibility would be redundant in this case as the next module to arrive would be of suitable type for the slot to which the disrupted module was assigned.

Proposition: *Lateral assignment flexibility performs equally well compared to lateral sequence flexibility should there be a single module type per floor.*

6.2.5.3 *Impact of different combinations of on-site installation flexibility*

Figure 6-17 shows the effect of enabling different on-site installation flexibility combinations on the mean percentage reduction in delay compared to not having any flexibility enabled.

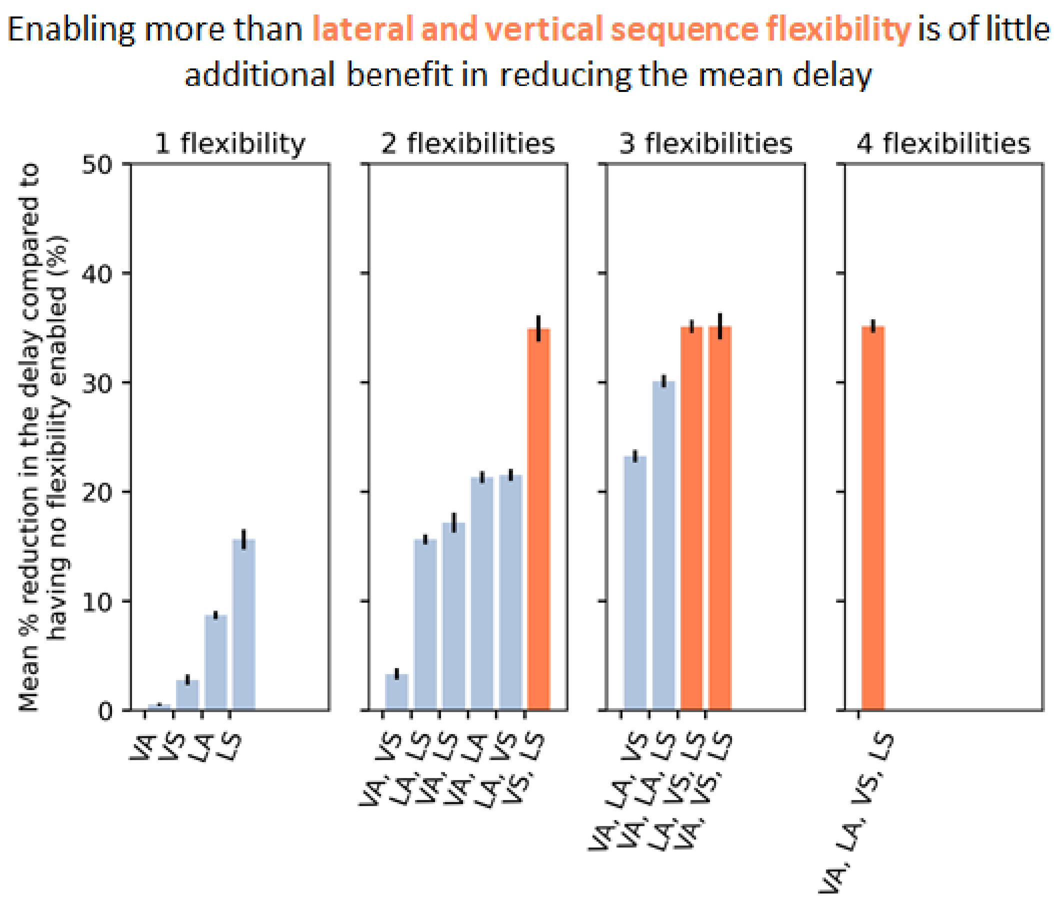

Figure 6-17: Effect of different flexibility types and combinations on mean percentage reduction in the delay compared to not having any flexibility enabled (VA = Vertical assignment flexibility; LA= Lateral assignment flexibility; VS = Vertical sequence flexibility; LS = Lateral sequence flexibility).

A bootstrap method was used to compute the percentile confidence intervals (lower 2.5 and upper 97.5 percentile) of the mean values reported in this figure (and relevant ones below). These were constructed by creating 100,000 bootstrap samples of the same size as the number of replications which made up the distributions from which the mean values displayed on this figure were calculated. The percentile confidence intervals are shown as error bars.

The combinations were clustered together according to the number of flexibilities enabled in each combination. On average, enabling more on-site installation flexibility increased the mean percentage reduction in the delay. The best mean percentage reduction in the delay achievable was 35.16%. What is more, combining any lateral flexibility and any vertical flexibility always results in a performance greater than the sum of that for the individual flexibilities.

Proposition: *Combining any lateral and any vertical on-site installation flexibility can result in a reduction in delay greater than the sum for the individual flexibilities.*

It is also of interest to decision makers to note that enabling more flexibilities did not always result in an increased reduction in the mean percentage delay. Indeed, from Figure 6-17 it is apparent that enabling any more than lateral and vertical sequence flexibility resulted in an almost negligible increase in percentage reduction in the delay. This result may be case specific, as different building layouts and module type compositions may affect the relative performance of each flexibility combination.

Proposition: *Enabling additional flexibilities on top of lateral and vertical sequence flexibility is of little benefit in terms of improving the mean percentage reduction in delay.*

Figure 6-18 gives an overview of the best mean percentage reduction in delay that can be achieved by picking the most suitable combination of flexibilities for each combination of disruption conditions. A similar phenomenon in Figure 6-18 to that in Figure 6-11[13] can be observed where a marked shift in the results occurred at a probability of module disruption of 0.06, indicated by line A. Any change from this value of probability diminished the mean percentage reduction in installation time. A detailed

[13] Note that Figure 6-18 plotted mean percentage reduction in total installation time whereas Figure 6-11 plotted installation delay.

explanation for this behaviour is provided in Appendix D.1.1. The mean percentage reduction varied significantly for different combinations of probability and disruption. The best mean percentage reduction in installation time was 13.19% at disruption probability 0.06 and duration 20 time units. As such, on-site installation flexibility has been shown to have potential to improve performance of modular off-site construction systems under a range of different disruption conditions.

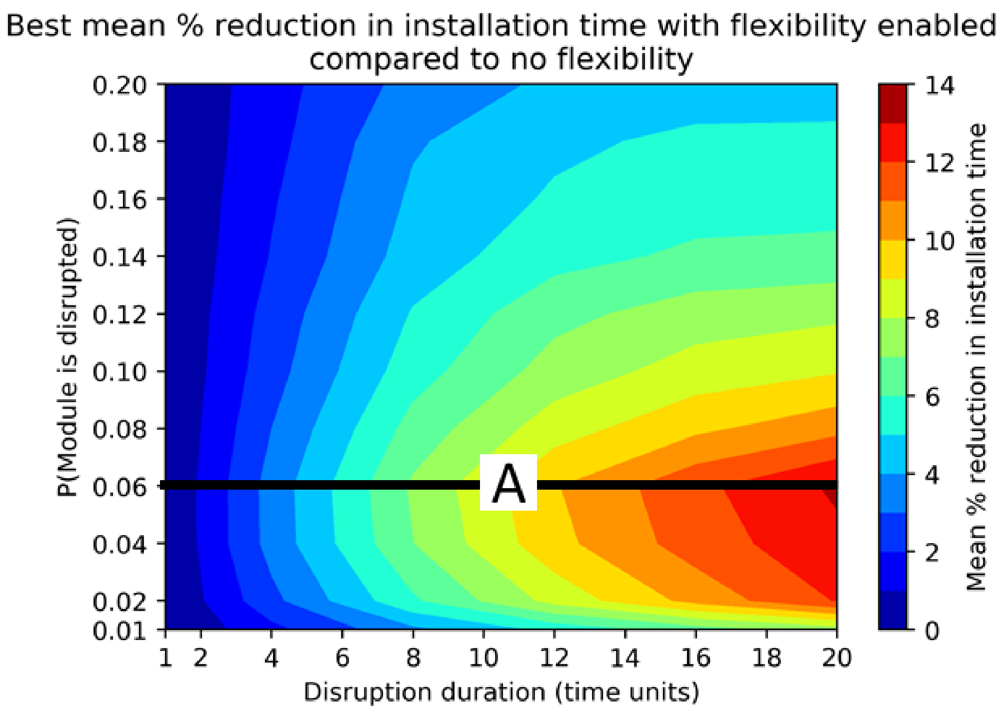

Figure 6-18: Maximum achievable mean percentage reduction in installation time by enabling flexibility compared to no flexibility.

This section has shown the behaviour of the system in terms of installation time and delay reduction over a range of different disruption conditions. Combinations including lateral and vertical sequence flexibility were found to be the most effective in reducing the installation delay. However, as is explored in the next section, other flexibility combinations can benefit the system in other ways.

6.2.6 Impact of on-site installation flexibility on other performance metrics

In this section, the effect of different flexibility combinations on buffer performance metrics, total floor completion delay, and nominal installation sequences are analysed.

6.2.6.1 *Impact of on-site installation flexibility on buffer metrics*

Figure 6-19 and Figure 6-20 show that all on-site installation flexibility combinations had the potential to reduce significantly not only the buffer size required to store modules when a disruption occurred but also the total module dwell time in the buffer (i.e. the sum of the time periods all the modules spend in the buffer). Indeed, mean percentage reductions in the maximum number of modules in the buffer of up to 61% and the module dwell time of up to 71% were achieved. This is because installation flexibility increased the possibilities of installing a module, thereby reducing the amount of time modules needed to spend in the buffer. What is more, when analysing the range of results, it was found that in some cases it was possible to entirely remove the need for a buffer (i.e. 100% reduction in module dwell time and maximum number of modules in the buffer). This is a useful finding for practitioners given that land for storing large modules is scarce and expensive, particularly near urban building sites.

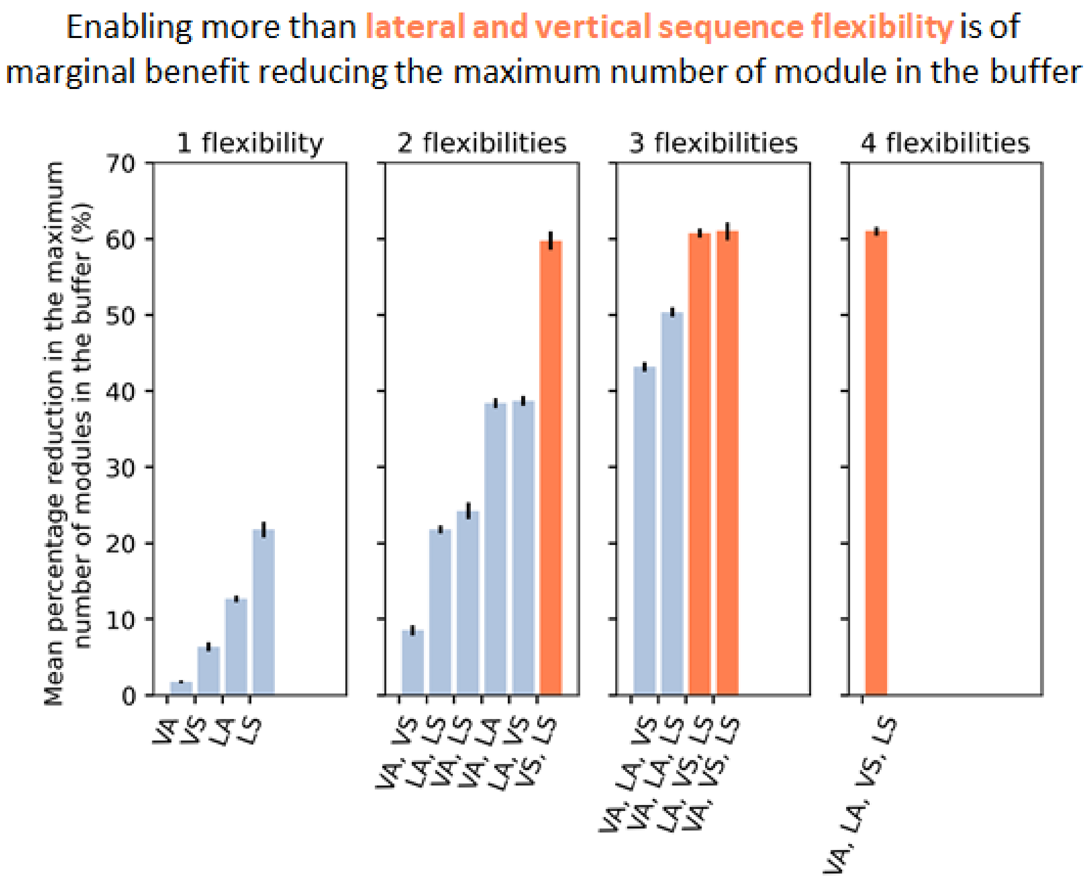

Figure 6-19: Effect of different flexibility types and combinations on mean percentage reduction in the maximum number of modules in the buffer (VA = Vertical assignment flexibility; LA= Lateral assignment flexibility; VS = Vertical sequence flexibility; LS = Lateral sequence flexibility).

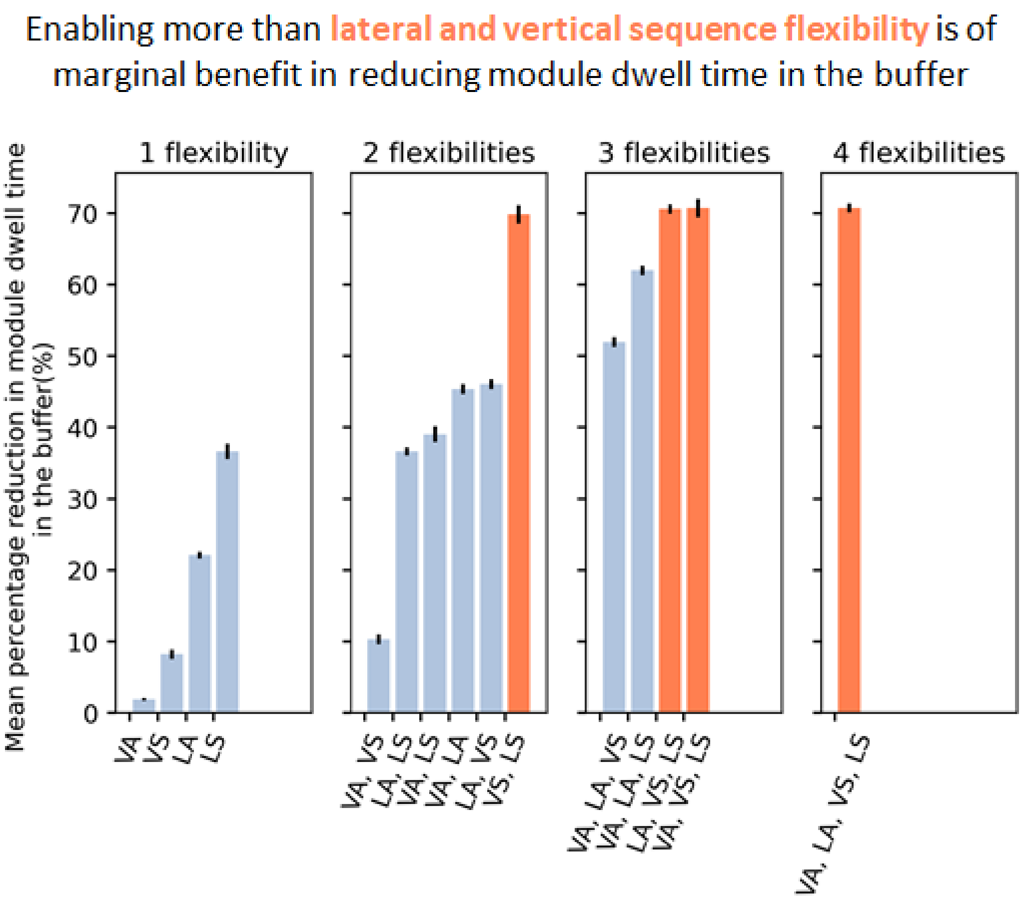

Figure 6-20: Effect of different flexibility types and combinations on mean percentage reduction in module dwell time in the buffer (VA = Vertical assignment flexibility; LA= Lateral assignment flexibility; VS = Vertical sequence flexibility; LS = Lateral sequence flexibility).

Proposition: *On-site installation flexibility can significantly reduce the buffer size requirement as well as the total dwell time of modules in the buffer.*

It is also possible to see that there was little benefit in enabling more than lateral and vertical sequence flexibility (combinations with "VS, LS" indicated in orange) to improve the mean percentage reduction in module dwell time in the buffer and the maximum number of modules in the buffer. This is because, unlike assignment flexibilities, sequence flexibilities do not have constraints on the next module type that can be installed. That said, this result may be case specific, as different building layouts and module type compositions may affect the relative performance of each flexibility combination.

Proposition: *Enabling additional flexibilities on top of lateral and vertical sequence flexibility is of little benefit in terms of reducing the total module dwell time in the buffer and maximum number of modules in the buffer.*

6.2.6.2 *Impact of on-site installation flexibility on total floor completion delay*

Even though the total delay of a project was limited to the maximum feasible disruption duration, adding up the total of the delays for the completion of each individual floor could exceed this. For example, when no flexibility is enabled, if say the first module to be installed is delayed for a duration of 20 time units, the overall delay in the project will be 20 time units. However, each floor will be delayed by 20 time units, yielding a total floor delay of 80 time units. This obviously delays any work that can only be done once each individual floor has been completed, such as testing the MEP system. It is evident from Figure 6-21 that enabling various combinations of on-site installation flexibility had the effect of improving the mean total reduction in floor completion delay. Therefore, on-site installation flexibility can help to ensure that any subsequent planned work for a completed floor begins on time.

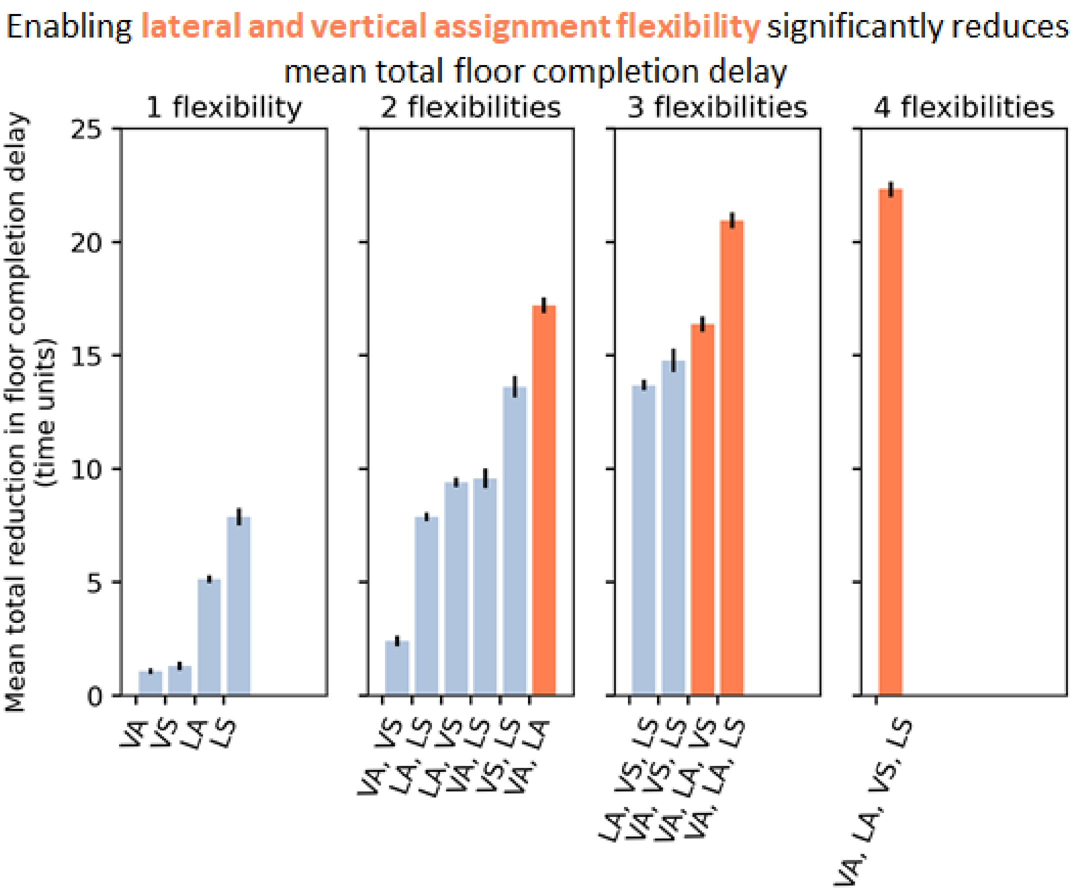

Figure 6-21: Effect of different flexibility types and combinations on mean total reduction in floor completion delay (VA = Vertical assignment flexibility; LA= Lateral assignment flexibility; VS = Vertical sequence flexibility; LS = Lateral sequence flexibility).

Proposition: *On-site installation flexibility can reduce the total floor completion delay, thereby permitting any work that can only begin once a floor is completed to start on time.*

In terms of mean total reduction in floor completion delay, Figure 6-21 shows that enabling vertical and lateral assignment flexibility together (highlighted in orange) outperformed other combinations. That said, it can also be observed that enabling more than those two flexibilities did not necessarily improve the total reduction in floor completion delay. For instance, the combination of vertical and lateral assignment flexibility (“VA, LA”) achieved a greater mean reduction in total floor completion delay than when vertical sequence flexibility was added (“VA, LA, VS”). Including vertical sequence flexibility allowed the system to begin installing modules on an upper floor while a disrupted module for the lower floor was being remedied. Consequently, fewer modules were immediately available from the buffer to complete the lower floor when the disrupted module arrived. Hence the upper floor progressed earlier than planned at the expense of being able to complete the lower floor. It should be noted that the observed behaviour may be case specific, as different building layouts and module type compositions may affect the relative performance of each flexibility combination.

<u>Proposition</u>*: The most effective combinations of on-site installation flexibility for mean reduction in the total floor completion delay always include both lateral and vertical assignment flexibility.*

6.2.6.3 *Impact of on-site installation flexibility on nominal installation sequence metrics*

The nominal module installation sequence is the order in which modules are installed in the building should no disruption occur. Similarly, the nominal slot installation sequence is the order in which slots have their modules installed should no disruption occur. Figure 6-22 and Figure 6-23 show that on-site installation flexibility resulted in a large percentage of modules and slots changing order from their respective nominal installation sequences. Hence, practitioners need to ensure greater control and co-ordination of on-site installation operations to avoid any errors occurring such as installing the wrong module in the wrong slot.

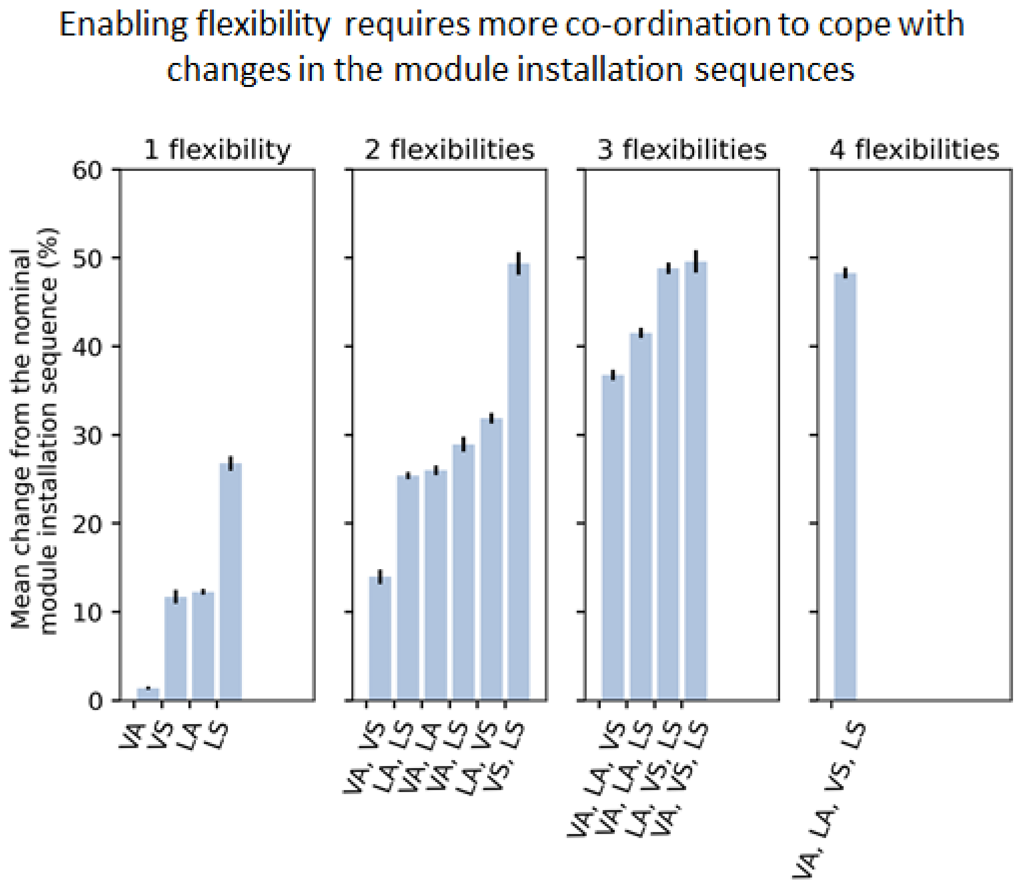

Figure 6-22: Effect of different flexibility types and combinations on mean percentage of modules that changed sequence from that in the nominal module/slot installation sequence (VA = Vertical assignment flexibility; LA= Lateral assignment flexibility; VS = Vertical sequence flexibility; LS = Lateral sequence flexibility).

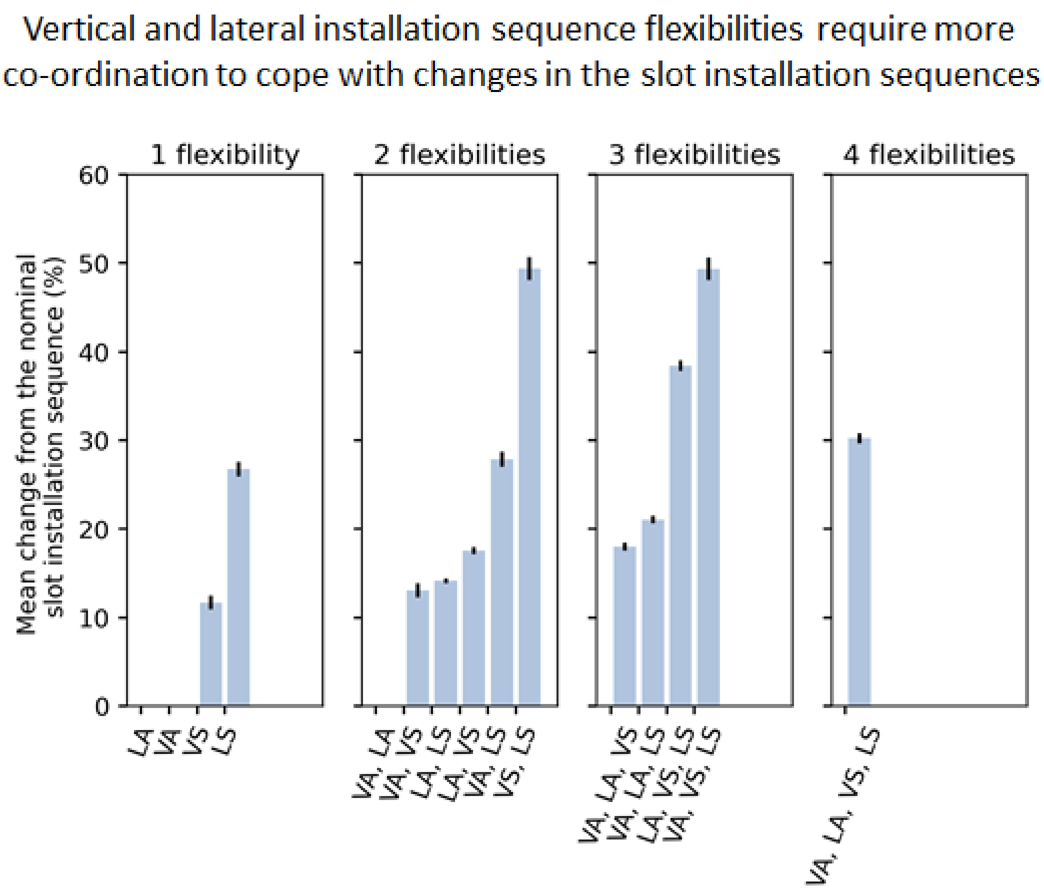

Figure 6-23: Effect of different flexibility types and combinations on mean percentage of slots that changed sequence from that in the nominal module/slot installation sequence (VA = Vertical assignment flexibility; LA= Lateral assignment flexibility; VS = Vertical sequence flexibility; LS = Lateral sequence flexibility).

***Proposition*:** *In general, the more on-site installation flexibilities that are enabled, the greater the control and co-ordination efforts required for the on-site module and slot installation operations.*

Figure 6-23 reveals several points of interest to decision makers. Firstly, when only assignment (as opposed to sequence) flexibilities were enabled, no changes were made to the nominal slot installation sequence. Secondly, when both assignment flexibilities were enabled in a combination, the mean percentage of changes from the nominal slot installation sequence was lower. Thirdly, when both sequence flexibilities were enabled in a combination, the opposite was true. To summarise, enabling more assignment and fewer sequence flexibilities generally resulted in fewer changes to the nominal slot installation sequence, thereby making on-site installation operations easier to manage as there is less additional co-ordination required between the factory and the site.

Proposition: *Enabling more assignment and fewer sequence flexibilities generally results in fewer changes in the nominal slot installation sequence thereby making on-site installation operations easier to manage.*

6.2.7 Summary of the findings

A number of propositions were put forward based on the results from this case study. Many of them can be expected to hold true for various building layouts and module compositions given that there is a logical explanation for the observed behaviours. These are summarised below:

1. **Without on-site installation flexibility, the choice of disruption management strategy depends on the likelihood of disruptions:** Without on-site installation flexibility, if it is not feasible to reduce the likelihood of a module being disrupted below a level where a disruption is not expected, decision makers should focus on reducing the duration of the disruption rather than the probability. If it is feasible to limit the probability of disruptions, decision makers should focus on further minimising both the likelihood and the duration of disruptions.
2. **Each type of on-site installation flexibility has characteristics that make it well suited to reducing delays in particular disruption conditions and projects:** Vertical assignment flexibility is useful in conditions where the disruption duration of a module is longer than the time it takes for a module of an identical type to be delivered to the site. Vertical sequence flexibility is most effective for systems where the installation time per floor is comparable to the expected disruption duration. It is more effective at reducing delays in multi-storey building projects. Lateral sequence flexibility is a good choice when the installation time per floor is large compared to the disruption duration of modules. The performance of lateral assignment flexibility improves as the number of modules of the same type on a given floor increases. Finally, lateral assignment flexibility performs equally well compared to lateral sequence flexibility should there be a single module type per floor.
3. **Combining more than one on-site installation flexibility can significantly improve the reduction in delay:** Combining any lateral and any vertical flexibility can result in a reduction in delay greater than the sum for the individual flexibilities.
4. **On-site installation flexibility can eradicate the need for a storage buffer:** On-site installation flexibility allows practitioners to reduce significantly or even completely eradicate the need for a buffer to manage disruptions.
5. **On-site installation flexibility can reduce the total floor completion time, minimising knock-on effects of disruptions:** All on-site installation flexibility combinations were found to be capable of reducing the total floor completion delay. This is of practical importance as if each floor has work which can only be undertaken once a floor has been completed (e.g. plumbing system tests), it would reduce the knock-on effects of any module disruption on such works.

6. **Using on-site installation flexibilities requires greater control and co-ordination of on-site installation operations:** The drawback of using on-site installation flexibilities is that greater control and co-ordination of on-site installation operations are required to ensure that the correct module is installed into the correct slot. Enabling more assignment and fewer sequence flexibilities generally results in fewer changes in the nominal slot installation sequence thereby making on-site installation operations easier to manage.

Some of the propositions that concerned the relative performance of different flexibility combinations would merit further investigation with different building layouts and module type compositions to see if they still hold true. Notably, the fact that enabling additional flexibilities on top of lateral and vertical sequence flexibility is of little benefit in terms of improving the mean percentage reduction in delay, total module dwell time in the buffer, and maximum number of modules in the buffer. This is also true for the proposition that the most effective combinations of on-site installation flexibility for mean reduction in the total floor completion delay always include both lateral and vertical assignment flexibility. That said, the building chosen in this case study is representative of a typical project.

An overview of the results for each metric and combination of on-site installation flexibility is given in Table 6.5. Green indicates better performance and red worse.

Table 6.5: Summary of the mean performance of different aspects of the system under different flexibility combinations (VA = Vertical assignment flexibility; LA= Lateral assignment flexibility; VS = Vertical sequence flexibility; LS = Lateral sequence flexibility).

	% reduction in module dwell time in the buffer	% reduction in maximum number of modules in buffer	% reduction in the delay	% modules which changed position in installation sequence	% slots which changed position in installation sequence	Mean total reduction in floor completion delay (time units)
LS	37	22	16	27	27	8
VS	8	6	3	12	12	1
LA	22	13	9	12	0	5
VA	2	2	1	1	0	1
VS, LS	70	60	35	49	49	14
LA, LS	37	22	16	25	14	8
LA, VS	46	39	22	32	18	9
VA, LS	39	24	17	29	28	10
VA, VS	10	9	3	14	13	2
VA, LA	45	38	21	26	0	17
LA, VS, LS	71	61	35	49	38	14
VA, VS, LS	71	61	35	50	49	15
VA, LA, LS	62	50	30	41	21	21
VA, LA, VS	52	43	23	37	18	16
VA, LA, VS, LS	71	61	35	48	30	22

6.3 Case study B: A social-housing apartment block

6.3.1 Operational context

A large multinational construction company secured the contract to construct a social-housing apartment block in the UK. The management of the company sought to understand whether it was economically worthwhile investing in on-site installation flexibility over more conventional disruption management strategies (or a combination of the two) in such a case. The approach proposed in Section 5.5 was used to analyse the problem.

6.3.2 Applying the approach

Step 1: Collect data on building layout and module characteristics

The building is made up of 45 apartments arranged across five storeys. The ground floor has 9 apartments, the three intermediate floors have 10 apartments each, and the top floor has 6 apartments. The floor plans can be seen in Figure 6-24. There are two types of apartments in the building with either a single- or double-bedroom layout. The apartments are made up of two modules, as shown in the floorplans in Figure 6-25. One module contains the living, dining, and kitchen area and the second module contains the bedroom and bathroom area. In total there are 90 modules inside the building.

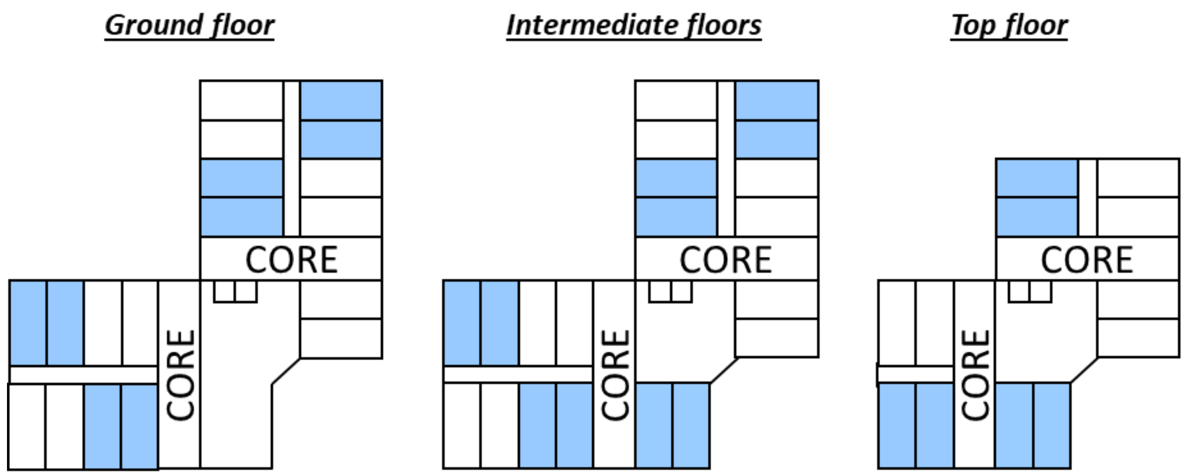

Figure 6-24: Floor plan of the building in Case Study B (blue shading is double bedroom apartment and white shading is single bedroom apartment layout).

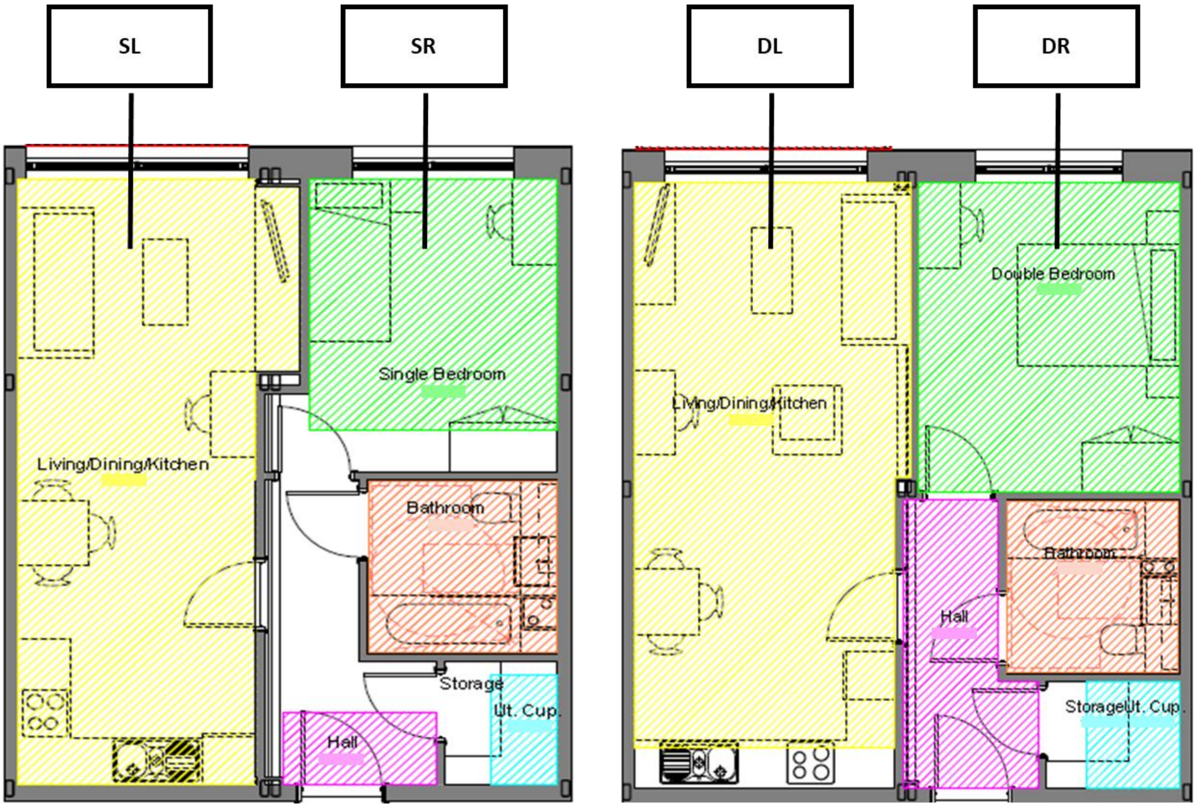

Figure 6-25: Single bedroom apartment floor plan on left and double bedroom on right (SL = Single bedroom left; SR = Single bedroom right; DL = Double bedroom left; DR = Double bedroom right).

Step 2: Determine installation flexibility options that are feasible

All flexibility types were determined to be worthwhile considering. Both vertical and lateral sequence flexibility were assessed as being feasible. This was also the case for vertical assignment flexibility where structural modifications to the modules would be required so that they could be placed on any floor. Three options for lateral assignment flexibility could be foreseen:

1. <u>Enabling assignment flexibility but not making any design changes to the modules</u>.
2. <u>Making SL and DL identical in terms of finish when they leave the factory</u>: where the bedroom modules SR and DR remain unique in terms of finish. This can be achieved by convincing the architects and the client to select a common module layout for SL and DL.
3. <u>Same as Option 2 only that SR and DR are also made identical in terms of finish when they leave the factory</u>: which would result in the greatest degree of lateral assignment flexibility. This could again be achieved by agreeing common module finishes.

A range of different module types could therefore be produced by the factory depending on which lateral assignment flexibility is selected and whether it is combined with vertical assignment flexibility. The resulting number of unique module types for each combination is outlined in Table 6.6.

Table 6.6: Number of unique module types produced by the factory for different assignment flexibility combinations.

Vertical assignment flexibility	Lateral assignment flexibility	# unique module types exiting the factory
No	Option 1	20 (4 types/floor x 5 floors)
No	Option 2	15 (3 types/floor x 5 floors)
No	Option 3	10 (2 types/floor x 5 floors)
Yes	Option 1	4
Yes	Option 2	3
Yes	Option 3	2
Yes	No	20

Step 3: Determine the cost to enable feasible on-site installation flexibilities

The costs of enabling each enabler identified in Table 4.4 were estimated and are broken down in Appendix Table D.1. Based on the findings in Chapter 4, potential cost efficiencies were factored in should the flexibilities of a given combination require a common enabler. If that were the case, then the cost of unlocking such an enabler would only be factored in once for a given flexibility combination. The costs of each flexibility combination were calculated and are shown in Table 6.7. In total there are 32 on-site installation flexibility combinations, including the case where no flexibility is enabled.

Table 6.7: Flexibility combination costs. Y= Yes; N = No.

Flexibility combination j	Cost (£)	Flexibility enabled?						# flexibilities enabled in combination j
		Installation sequence		Slot assignment				
		Vertical	Lateral	Vertical	Lateral option 1 (4 module types per floor)	Lateral option 2 (3 module types per floor)	Lateral option 3 (2 module types per floor)	
1	10650	N	N	Y	N	N	N	1
2	19364.75	Y	N	Y	N	N	N	2
3	19764.75	Y	Y	Y	N	N	N	3
4	14068.75	N	Y	Y	N	N	N	2
5	10650	N	N	Y	Y	N	N	2
6	19364.75	Y	N	Y	Y	N	N	3
7	19764.75	Y	Y	Y	Y	N	N	4
8	14068.75	N	Y	Y	Y	N	N	3
9	10650	N	N	Y	N	Y	N	2
10	19364.75	Y	N	Y	N	Y	N	3
11	19764.75	Y	Y	Y	N	Y	N	4
12	14068.75	N	Y	Y	N	Y	N	3
13	10650	N	N	Y	N	N	Y	2
14	19364.75	Y	N	Y	N	N	Y	3
15	19764.75	Y	Y	Y	N	N	Y	4
16	14068.75	N	Y	Y	N	N	Y	3
17	0	N	N	N	N	N	N	0
18	10964.75	Y	N	N	N	N	N	1
19	11364.75	Y	Y	N	N	N	N	2
20	5668.75	N	Y	N	N	N	N	1
21	6650	N	N	N	Y	N	N	1
22	15364.75	Y	N	N	Y	N	N	2
23	15764.75	Y	Y	N	Y	N	N	3
24	10068.75	N	Y	N	Y	N	N	2
25	6650	N	N	N	N	Y	N	1
26	15364.75	Y	N	N	N	Y	N	2
27	15764.75	Y	Y	N	N	Y	N	3
28	10068.75	N	Y	N	N	Y	N	2
29	6650	N	N	N	N	N	Y	1
30	15364.75	Y	N	N	N	N	Y	2
31	15764.75	Y	Y	N	N	N	Y	3
32	10068.75	N	Y	N	N	N	Y	2

Step 4: Depict the modular off-site construction system process flow

The modular off-site construction system that the company operates on a just in time basis to deliver modules to the site is depicted in Figure 6-26. Modules leave the factory and enter a quality assurance station where they are checked for any defects and incomplete work. Under no circumstance do decision makers want the factory production line to halt to rectify any such issues. Hence should there be a need to do so, the affected modules are sent to re-work bays to be finished to the required standard. From the point of view of the on-site installation operations, this means that each module can be viewed as having a certain probability of disruption for a certain duration. Once modules are completed, they are transported directly to the construction site and installed by a crane. However, in the event of a module being disrupted, installation constraints may make it necessary to store modules in an emergency storage area until the disrupted module (or another adequate module) is delivered to the site.

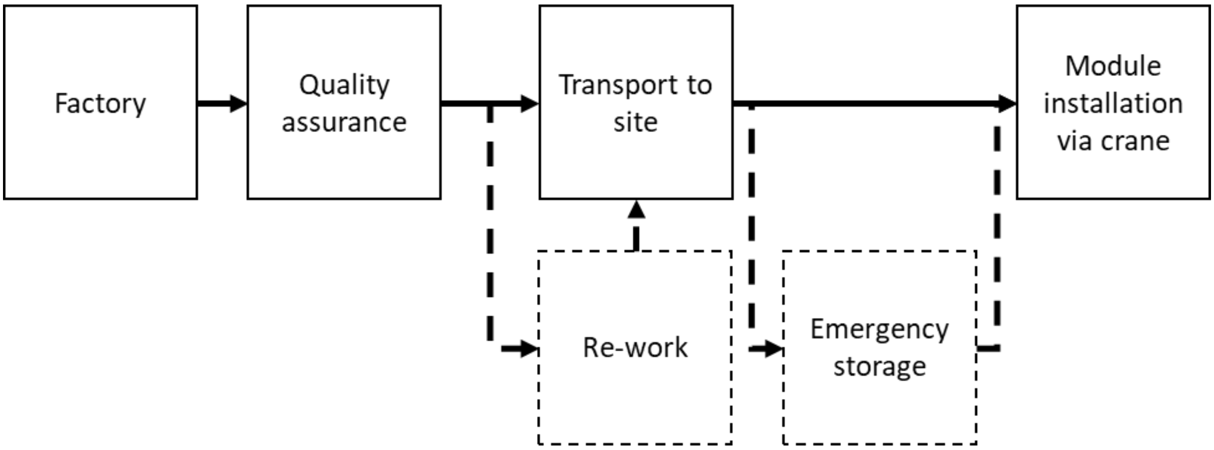

Figure 6-26: Overview of key elements of the modular off-site construction system used to manufacture the social-housing apartment block.

Step 5: Collect operational data on module disruptions and the various processes

Based on the opinion of company experts, it was estimated that each module had a 5% likelihood of being disrupted for a period of 24 time units. This seemed reasonable from discussions with other modular off-site companies mentioned in Chapter 3. Additional estimated cost and process time parameters are displayed in Table 6.8.

Table 6.8: Parameter values as estimated by decision makers for use in the model.

Parameter	Value
Factory takt time	1 time unit
Quality assurance process	1 time unit
Transport time from factory to buffer	1 time unit
Crane installation time per module	1 time unit
Project installation phase duration if there are no disruptions	92 time units
Re-work cost to fix module for disruption duration of 24 time units	£2084
Re-work cost to fix module for disruption duration of 16 time units	£1746
Re-work cost to fix module for disruption duration of 8 time units	£1408
Cost per time unit of delay	£1,324.87
Cost of security for permanent buffer storage	£97.2/time unit of installation time
Emergency storage cost	£39.29/module/time unit

Step 6: Determine any process improvement investment options and their costs

Three categories of process improvement options were considered by the experts: investing in a buffer, reducing the disruption likelihood, and reducing the disruption duration. They decided to make conservative cost estimates based on twenty projects per year. Firstly, there was an option to invest in a buffer that had a capacity of up to 24 modules. The rationale of investing in a buffer was that it could potentially reduce the need to rent emergency storage space, which is more expensive. The cost for various buffer capacities can be seen in Appendix Table D.2. Reducing the disruption likelihood could be achieved by investing in options such as additional training for factory labour, sourcing better quality parts that are less prone to failure, and improving supplier relationships to ensure parts are delivered on time. Reducing the disruption duration could be achieved by investing for instance in additional quality assurance personnel on the line to catch errors early so as to reduce the build-up of work, holding a stock of parts to replace ones that are prone to breakage or delay, and increasing the amount of labour available to repair errors. It was estimated that the duration of the disruptions could potentially be reduced by 8 or 16 time units and the likelihood of a module being disrupted could be halved to 2.5%. The costs of different combinations of disruption likelihood and duration reductions are detailed in Table 6.9.

Table 6.9: Estimated annual costs of different combinations of disruption likelihood and duration options.

Disruption mitigation option i	P(Module disrupted)	Disruption duration (t.u.)	Estimated annual costs (£)
1	0.025	8	132,000
2	0.025	16	96,000
3	0.025	24	60,000
4	0.05	8	72,000
5	0.05	16	36,000
6	0.05	24	0

Step 7: Determine objective function

The objective function was defined in Section 5.4.3 (shown again below for convenience):

$$\max\left(\sum_{i}\sum_{j}\sum_{k}\left(\left[(1-\beta)median\left(S_{ijk}\right)-\beta MAD\left(S_{ijk}\right)\right]\times z_{ijk}\right)\right), \qquad 0\le\beta\le 1$$

where S_{ijk} is the cost saving distribution for disruption mitigation improvement combination option i, on-site installation flexibility combination j, and buffer capacity level k. z_{ijk} is the binary decision variable for the optimal choice of investment.

Steps 8-13:

$\beta = 0.15$ was chosen, given the preference to maximise the median cost saving rather than a high aversion to risk (accounted for by the median absolute deviation in cost saving). This is within the range used by (Tomlin, 2006; Liu and Nagurney, 2011). No modification to the DES model was required. The output of the DES was deemed to be adequate using validation techniques outlined in Section 5.4.4. 50 replications were conducted for each possible combination of ijk. Similar DES studies used numbers of replications between 10 and 100 (Padhi *et al.*, 2013; Vidalakis, Tookey and Sommerville, 2013; Arashpour *et al.*, 2015; Goh and Goh, 2019).

Step 14: Select best combination of on-site installation flexibility and process improvement options

A sensitivity analysis was conducted for a step increment of 0.01 from $\beta = 0$ to $\beta = 1$ to reassure decision makers on the choice of β. The median cost saving for the optimal investment combination ijk for each value of β is plotted on Figure 6-27. In addition, the mean absolute deviation (MAD) away from the median cost saving is also plotted as the dashed lines for each combination.

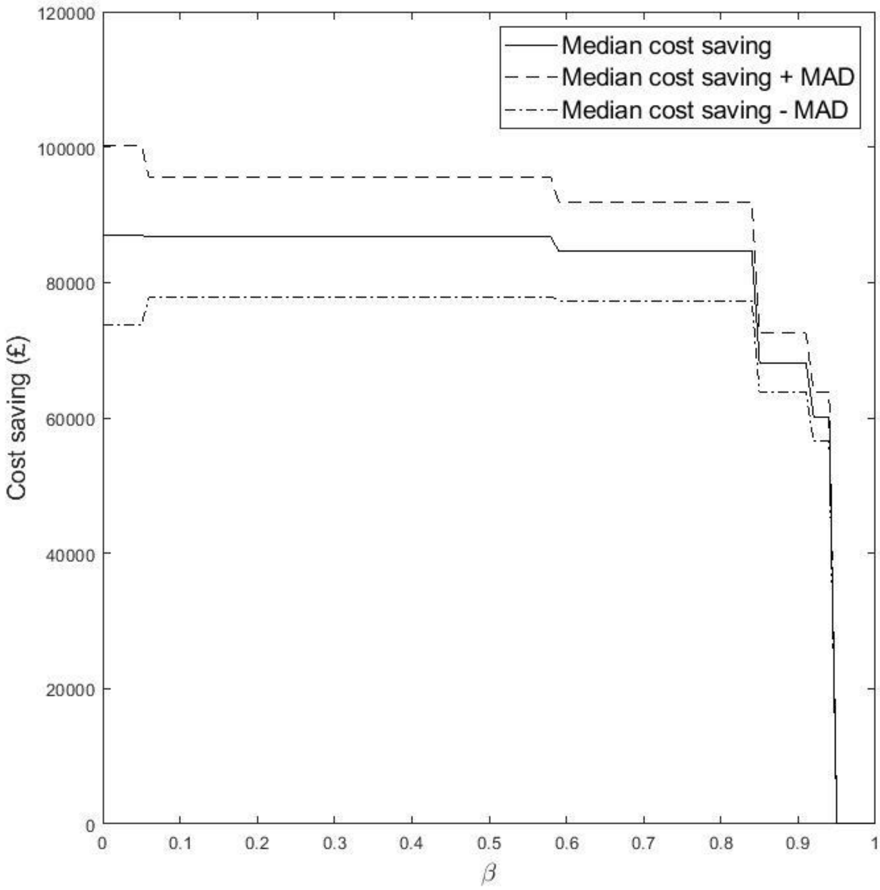

Figure 6-27: Median cost saving ± MAD for the optimal choice of process improvements and on-site installation flexibility combinations for each beta between 0 and 1.

As can be expected, with increasing β the MAD of the optimal solution reduces, given that a higher β implies being more risk averse in terms of cost certainty. From $0.06 \leq \beta \leq 0.58$, the optimal choice of investments (i.e. ijk) remains the same. For $\beta \leq 0.05$, the optimal choice would be to make the same investment decision but without vertical installation sequence flexibility – i.e. only lateral sequence flexibility ($j = 16$). However, for this range the MAD represents ± 15.3% of the median whereas for $0.06 \leq \beta \leq 0.58$, it is ± 10.1% for a drop in median cost saving of 0.3%. Hence the optimal solution recommended by the model at the chosen $\beta = 0.15$ is robust to changes in β:

- Invest in disruption mitigation improvement option $i = 1$, where the disruption duration and likelihood are minimised as much as possible.
- Invest in installation flexibility combination $j = 19$, where both lateral and vertical installation sequence flexibility are enabled.
- Do not invest in a permanent buffer (i.e. $k = 0$).

Such investments would result in a median cost saving of £86,693.50 with a median absolute deviation of £8,771.50.

The fact that a permanent buffer is not required is noteworthy as it means that because of on-site installation flexibility, it is possible for companies to forego the need of having a permanent buffer and still achieve a good performance. This finding is potentially highly beneficial for modular off-site construction companies that may have projects in dispersed locations where the cost of finding and investing in a plot of land for storage close to a site only for it not to be used for many other projects is wasteful. Furthermore, it may not always be possible to find land in a location near a site, particularly in densely packed urban areas.

6.3.3 Summary of the findings

In this case study, the approach developed in Section 5.5, was demonstrated by applying it to a social housing modular off-site construction project. The following propositions can be drawn from the findings:

- The use of on-site installation flexibility could provide cost savings on modular off-site construction projects.
- The use of on-site installation flexibility could allow decision makers to forego the need for a permanent buffer and still achieve cost savings. This is particularly useful for modular off-site construction projects where finding a suitable buffer storage location may not be possible.

This case study also showed that the approach was applicable to a real industrial scenario.

6.4 Summary

The objectives of this chapter were to gain insight into the behaviour of on-site installation flexibility and assess its value for disruption management in modular off-site construction. In doing so, the model and the decision-making approach devised in Chapter 5 were demonstrated in two industrial case studies.

The first case study explored the behaviour of a modular off-site construction system enabled by different combinations of on-site installation flexibility for a range of disruption conditions. The installation phase of a typical high-end residential apartment block carried out by a multinational construction company was simulated from which several propositions were put forward. It was found that:

- On-site installation flexibility can not only reduce installation delays but also the total floor installation completion delay and even remove the need for a buffer. This is particularly interesting for modular off-site construction companies that build projects in densely packed urban areas where suitable storage space is both limited and expensive.
- Each type of on-site installation flexibility has characteristics that make it well suited to reducing delays in particular disruption conditions and projects.
- Combining more than one type of on-site installation flexibility could significantly improve the reduction in delay.
- There are drawbacks and limitations of using on-site installation flexibility. Most notably there is a need for greater control and co-ordination of on-site installation operations to ensure that the correct module is installed into the correct slot, given the real-time deviations from the nominal module and slot installation sequences.

The focus of the second case study was on demonstrating the value of on-site installation flexibility in an industrial context where alternative disruption management options were available. The case study concerned the investment decision for a social-housing apartment block project. Using the approach devised in Chapter 5, it was found that:

- On-site installation flexibility is a financially viable method of improving system performance.
- The use of on-site installation flexibility could allow decision makers to forego the need for a permanent buffer and still achieve cost savings.

This chapter demonstrated the usefulness of the Discrete Event Simulation model and the decision-making approach developed in Chapter 5 when applied to two industrial case studies. To conclude, on-site installation flexibility has the potential to be a valuable addition to the conventional disruption management options available to the modular off-site construction industry.

Chapter 7: Conclusions and future research

7.1 Summary of research

This research investigated disruption management in modular off-site construction. It is motivated by the recent drive in the construction industry to modernise operations and increase productivity. Modular off-site construction is said to be one of the ways in which this can be achieved. Managing modular off-site construction operations will become more challenging in the future, with shorter factory takt times and larger project sizes. It is therefore essential to have effective strategies to counter disruptions to avoid being faced with significant project time and cost overruns as a result of halting site installation, requiring modules to be stored and even factory production to be suspended.

The review of literature on disruptions and disruption management strategies in modular off-site construction in Chapter 2 showed that little research had been conducted in this area. To address this gap, the first research question was to identify the main operational disruptions and disruption management strategies. Consequently, a qualitative study was undertaken in which experts from five modular off-site construction companies were interviewed. Furthermore, a workshop with industry practitioners was conducted. The main operational disruptions and disruption management strategies that they used were identified as well as their shortcomings, including the over-reliance on module storage and the lack of strategies to tackle particular challenges faced by the industry. To address these shortcomings, a novel, flexibility based, disruption management strategy was proposed: on-site installation flexibility.

There are two overarching types of on-site installation flexibility: slot assignment flexibility and slot installation sequence flexibility. Each come in two variants, lateral and vertical, and hence there is a total of four types of on-site installation flexibility. On-site installation flexibility relaxes the fixed on-site installation constraints that restrict the assignment of modules to slots and the sequence in which slots have their assigned modules installed. Based on this, three further areas of research were investigated: how a company can enable on-site installation flexibility (RQ2), how practitioners can decide on the appropriate level of on-site installation flexibility in a disruption management context (RQ3), and how it affects the behaviour of modular off-site construction systems (RQ4).

The focus of Chapter 4 was on addressing RQ2. A workshop was organised with practitioners from a modular off-site construction company to identify the enablers of each type of on-site installation flexibility as well as the interdependencies between them using an Impact Matrix Cross-Reference Multiplication Applied to a Classification (MICMAC) analysis. Interpretive Structural Modelling was used to create implementation roadmaps to guide practitioners interested in enabling on-site installation flexibility.

An approach to evaluate and select the appropriate level of on-site installation flexibility in a disruption management context was then devised in Chapter 5 to address RQ3. It involved the use of a Simulation-Based Optimisation (SBO) that combined a Discrete Event Simulation (DES) model with an Integer Linear Program. To answer RQ4, the behaviour of on-site installation flexibility was then investigated in Chapter 6 by applying the DES model to a case study of a high-end residential apartment block that had many dissimilar modules. The SBO approach was then demonstrated by applying it to a case study of a social-housing apartment block that had a smaller variety of modules. The case studies showed that on-site installation flexibility has benefits in reducing project delays and the need for storage space, but at the expense of more complex on-site operations.

7.2 Conclusions

7.2.1 Revisiting the research questions

Research Question 1: What are the main operational disruptions faced by the modular off-site construction industry and how do companies currently cope with such disruptions?

To answer this research question, interviews and factory visits with experts from five case study companies were conducted and an industrial workshop was held. In all, 23 experts from the modular off-site construction industry contributed to the findings of this study, as reported in Chapter 3.

With respect to the first part of this question, sixteen main operational disruptions were identified (see Table 3.6). They spanned the range of a modular off-site construction company's operations: those inbound to the factory, within the factory, between the factory and the construction site, and at the site. The most commonly reported disruptions were *Material not delivered on time to the* *factory*, *Component damage during production*, *High-wind conditions at the site*, and *Foundations not being completed on time*. That said, the companies did not all face the same set of disruptions.

With respect to the second part of the question, nine disruption management strategies were reported to be used (see Table 3.6). Modular off-site construction companies manage to cope with their main operational disruptions but still must accept delays. On average, the modular off-site construction companies had at least one disruption management strategy to address between three-quarters and all of the disruptions that they named. In addition, it was found that companies used different sets of disruption management strategies to counter the same disruptions.

Research Question 2: How can on-site installation flexibility be enabled?

To address this question a workshop was organised with experts from a multinational modular off-site construction company who had between 10 and 15 years of construction experience. The experts worked in a range of functions from product design to construction site operations management.

It was concluded from the discussions that on-site installation flexibility can be enabled by implementing different combinations of between 35 and 42 enablers depending on the chosen flexibility type. These enablers span across an entire organisation's functions, from securing top management support to updating quality assurance protocols at the construction site. When enabling on-site installation flexibility, it is important to do so in a structured manner because it was found that decisions relating to some enablers depend on decisions made for other enablers. To help guide practitioners through the order in which each enabler should be considered, implementation roadmaps for each of the four flexibility types were created. There is a significant degree of overlap between the enablers required for each. Indeed, 45% of the identified enablers are common to all flexibility types.

Research Question 3: How can the appropriate level of on-site installation flexibility be selected to support effective disruption management?

The challenge for practitioners is to decide on the appropriate level of on-site installation flexibility to implement when balanced against other disruption management options to minimise the overall cost of their operations. To address this question, an approach using a Simulation-Based Optimisation model was devised. The SBO model incorporated a Discrete Event Simulation model to capture the system behaviour accurately (e.g. on-site installation constraints) as well as the uncertainty in the number and timing of disruptions. An Integer Linear Program was then developed to feed on the results from the DES model and select the most appropriate combination of disruption management options, taking account of the degree of risk-adversity of the decision makers.

The approach brings together findings from different parts of this research:

- Chapter 2: The characteristics of modular off-site construction systems identified during the case study visits described in Section 2.3. These are used to determine the key elements and features to incorporate into the DES model.
- Chapter 3: The disruptions and disruption management strategies identified and reported in Table 3.6. The table is used as a prompt for practitioners to consider the range of disruptions that they may face and determine the likelihood a module is disrupted as well as the duration of such a delay. Furthermore, it helps practitioners consider different disruption management strategies in which they could invest as an alternative to, or in combination with enabling on-site installation flexibility.
- Chapter 4: The required enablers (Table 4.4) and the implementation roadmaps (Figure 4-6, Figure B-2, Figure B-3, and Figure B-4) for each type of on-site installation flexibility. These help practitioners determine whether each type of on-site installation flexibility is feasible. They provide a list of enablers for which the costs must be calculated to arrive at the overall cost of enabling each type of installation flexibility and eventual combinations of different on-site installation flexibilities. They also help identify opportunities for cost savings when enabling two or more types of on-site installation flexibility at the same time.

The DES was first used to investigate the behaviour of a system enabled by on-site installation flexibility by applying it to a high-end residential apartment block case study. The overall SBO approach was then demonstrated for the disruption management decisions faced by practitioners when applied to a social-housing apartment block project.

Research Question 4: How does on-site installation flexibility affect the behaviour of modular off-site construction systems?

The behaviour of modular off-site construction systems enabled by on-site installation flexibility was investigated by modelling the impact of the flexibility on several measures of interest to practitioners: project delay (or installation duration), buffer metrics, total floor completion delay, and changes from the nominal module and slot installation sequences. On-site installation flexibility affects the behaviour of modular off-site construction systems to varying degrees depending on: i) the type of on-site installation flexibility enabled, ii) the disruption conditions, and iii) the building configuration.

When on-site installation flexibility is enabled, the installation delay remains unchanged or it decreases. The magnitude of the decrease depends on the type of on-site installation flexibility chosen, as shown in Figure 6-17. What is more, the disruption conditions also influence the effectiveness of the flexibility in reducing the delay. For example, vertical assignment flexibility is only effective when the disruption duration is longer than the time it takes for the factory to produce and deliver a whole floor of modules, as reported in Section 6.2.5.2. Finally, the configuration of a building also has an effect. For instance, when lateral assignment flexibility is enabled, the more modules there are of a given type on a floor, the more likely that a module of the same type as a delayed module can be re-assigned to the delayed module's slot.

A similar pattern of behaviour is observed for decreases in the maximum number of modules in the buffer, the total module dwell time in the buffer, and the total floor completion delay. In contrast, the number of changes from the nominal slot and module installation sequences is negatively correlated with the other metrics. This is because the flexibility to fill the slots in a different order and with different modules inevitably leads to a deviation from what was nominally planned before a disruption occurs.

7.2.2 Summary of key findings

The key findings of this thesis are as follows:

1. **There is a need to find more effective disruption management strategies for modular off-site construction.**

   Experts mentioned clear shortcomings with current strategies to cope with disruptions. There were several disruptions for which they had no disruption management strategy. Two explanations for this were mentioned. Firstly, the drawbacks of some potential disruption management strategies outweighed their benefits. For example, investments in cross training labour to counter labour shortages were often lost as the newly certified personnel left for better jobs or to work for themselves. Secondly, the disruptions were sometimes beyond the control of the company and little could be done to manage them. For example, traffic accidents on the module's transport route were beyond the control of a company.

In addition, current disruption management strategies do not effectively mitigate all disruptions. Most of the disruption management strategies that have been employed could not be implemented at every occurrence of a disruption or had other drawbacks. For example, substituting a damaged component for one of a similar performance level is typically only acceptable for a component that is not visible to the building occupants. A further example is that re-work allows modules to be completed off-line while production on the main line continues. However, the overall project would still suffer a delay until the module is completed, albeit a less severe one. Practitioners therefore reported that even though companies may be aware of available disruption management strategies and use them when possible, a delay is often inevitable when disruptions occur.

Because of such drawbacks, there is an over-reliance on storing modules as a disruption management strategy. However, storage increases the risk of further disruptions occurring owing to the modules being damaged because of exposure to the elements as well as distortion from repetitive loading and unloading.

This over-reliance is of concern given that storing modules will become a less viable disruption management strategy as the industry grows. During this study, one company stated that its new factory would achieve production rates six times faster than current rates in the industry. Furthermore, project sizes are forecast to become much larger than those at present. Any prolonged disruption to such projects would result in storage areas quickly filling to capacity at which point either factory production would have to be halted, or costly emergency storage solutions would be needed.

2. **Creating disruption management strategies exploiting unique characteristics of modular off-site construction systems can be beneficial in addressing industry-specific challenges.**

For example, one such challenge in the modular off-site construction industry is the knock-on delays to modules that cannot be installed because of the on-site installation constraints. These constraints (e.g. modules for the first floor may not be installed until those of the ground floor have been installed) mean that if a module is delayed, then all modules following it in the installation sequence must be held back in storage, further increasing the strain on storage space. Only one disruption management strategy was reported to address this issue. *Sending a module to site partially finished* from the factory exploits a unique characteristic of modular construction systems whereby it is not necessary to fully finish a module at the factory before sending it to the site. For example, if a component does not arrive on time to be fitted at the factory, it can instead be sent to the site and fitted there. The benefit is that the installation at the site may continue as the module is no longer held up, but the downside is that it costs more to complete as on-site work is less efficient and quality control may be lower.

3. On-site installation flexibility is an effective disruption management strategy.

Four different types of on-site installation flexibility were proposed and evaluated: lateral and vertical assignment flexibility, and lateral and vertical sequence flexibility. On-site installation flexibility functions by relaxing different aspects of the on-site installation constraints. Assignment flexibility allowed for modules to be re-assigned to other slots and hence exchange places with other modules. Sequence flexibility allowed the sequence in which slots were filled with modules to be changed over the duration of a project.

The different on-site installation flexibility types were found to be effective disruption management strategies for several reasons. Most importantly, they can reduce the installation duration of a project that is affected by disruptions. They can also significantly reduce the reliance on module storage as a disruption management strategy in two ways. Firstly, they can reduce the overall buffer capacity requirements by reducing the maximum number of modules needed to be stored at any given time during the project. Secondly, they can reduce the total module dwell time in the buffer, reducing the risk of damage owing to exposure to the elements and reducing any emergency storage costs. They can sometimes even completely remove the need for any module storage. What is more, because on-site installation flexibility allows the installation at the site to continue, it can reduce the total floor completion delay. Consequently, it mitigates any knock-on delays on work that can only be undertaken after each floor is completed (e.g. testing MEP systems).

4. **Combining more than one type of on-site installation flexibility can significantly improve the performance of modular off-site construction systems.**

As reported in Sections 6.2.5.3 and 6.2.6, combining more than one type of on-site installation flexibility can significantly improve the above-mentioned metrics. That said, there are diminishing returns on performance improvements as additional on-site installation flexibility types are enabled. It was also found that certain combinations of on-site installation flexibility types perform better than others. For example, combining any lateral and vertical variants of on-site installation flexibilities together results in a mean reduction in delay greater than the sum of the individual flexibilities. This is because they complement each other by relaxing different aspects of the on-site installation constraints.

5. **Operating a system enabled by on-site installation flexibility requires additional control and co-ordination.**

Despite the above benefits, on-site installation flexibility requires a greater level of control and co-ordination between the site and the factory. Slot assignment flexibilities require greater effort than slot installation sequence flexibilities given that not only does the module installation sequence but also the slot installation sequence differ from the nominal sequences. In practical terms, when the module installation sequence differs, the installation teams must ensure that the correct module is selected to be hoisted into place by the crane. When the slot installation sequence differs, the installation team must ensure that the module is installed in the correct slot in the building.

6. **Implementing on-site installation flexibility requires co-ordination across a range of organisational functions.**

Enabling on-site installation flexibility requires several changes in a modular off-site construction company. Meetings with cross-functional teams are likely to be required to make decisions on enablers given that: i) enablers span the breadth of functions across an organisation, and ii) enablers are highly interdependent and hence any decision made for one enabler will have a bearing on decisions made for other enablers later in the implementation process. When enabling more than one on-site installation flexibility and given that 45% of enablers are common across all flexibility types, decisions regarding individual enablers are more complicated given that more factors need to be considered. However, combining installation flexibilities presents the opportunity to achieve cost-efficiencies in the implementation process.

7.3 Research contributions

In this section the main contributions of this research are presented. They are divided into academic and industrial contributions although the two are clearly linked.

7.3.1 Academic contributions

Recalling the research gaps identified in Section 2.5.1:

Research Gap 1: There has been little research on identifying operational disruptions faced by modular off-site construction companies and disruption management strategies used to mitigate them.

Research Gap 2: There is a lack of disruption management strategies tailored to the specific needs of the modular off-site construction industry as well as tools to select and assess them.

Several academic contributions (AC) were made by this research to help bridge these gaps:

1. **Qualitative study of the main operational disruptions and disruption management strategies used by modular off-site construction companies:** This study is detailed in Chapter 3 and contributes to literature by providing a mapping of the main operational disruptions that were identified to the disruption management strategies used by companies to counter them. *Send module to site partially finished* from the factory was found to be a disruption management strategy that is unique to the modular off-site construction industry. In addition, shortcomings of the current strategies were reported.
2. **Proposition of a novel disruption management strategy of on-site installation flexibility:** This aspect of the research contributes to modular off-site construction disruption management literature by putting forward a novel, flexibility based, disruption management strategy to

cope with disruptions. This strategy was explained in Section 4.3, and can be split into four types. *Vertical assignment flexibility* is the ability to install a module on a floor other than the one for which it was originally intended. *Lateral assignment flexibility* is the ability to install a module in a different slot from the one originally intended on the same floor. *Vertical sequence flexibility* is the ability to install a module on an upper floor while a lower floor is not yet finished. *Lateral sequence flexibility* is the ability to install modules on the same floor in more than one slot installation sequence. More specifically, this research contributes an additional strategy to the ones based on sequence flexibility that were identified in the review of Section 2.4.3.

3. **Implementation roadmaps for each type of on-site installation flexibility:** Given that on-site installation flexibility has only just been proposed, implementation roadmaps, created using Interpretive Structural Modelling, contribute to literature by providing insight into the practical changes an organisation must implement to enable on-site installation flexibility. The identification of the enablers and the development of the roadmaps are detailed in Chapter 4.
4. **Evaluation of the behaviour of modular off-site construction systems enabled by on-site installation flexibility:** A DES model was developed in Chapter 5 and applied to an industrial case study in Section 6.2. The behaviour of the system was evaluated by assessing the impact of on-site installation flexibility on various performance metrics under different disruption conditions. The summary of the findings of this analysis was presented in Section 6.2.7.
5. **An approach to selecting the appropriate level of on-site installation flexibility in a disruption management context:** A fourteen step approach was developed in Section 5.5, and demonstrated in an industrial case study in Section 6.3. The approach aids decision makers to weigh up the benefits of investing in on-site installation flexibility against, or in combination with, the benefits from adopting other disruption management strategies.

To summarise, Table 7.1 shows the research gaps that each academic contribution helps to address.

Table 7.1: Mapping of how each academic contribution helped bridge the research gaps identified in Section 2.5.1. X = Academic contribution that helps to bridge corresponding research gap.

Academic contribution (AC)	Research Gap 1	Research Gap 2
1	X	
2		X
3		X
4		X
5		X

Collectively, the contributions address the research aim of investigating operational disruptions (AC 1) in modular off-site construction and identifying (AC 1), proposing (AC 2), and assessing (AC 3, 4, and 5) disruption management strategies to mitigate them.

7.3.2 Industrial contributions

The industrial contributions of this thesis are as follows:

1. Practitioners can make use of the mappings in Table 3.6 of the main operational disruptions to disruption management strategies when evaluating the risks that they may face during a modular off-site construction project and how they may set about mitigating them.
2. This thesis provides practitioners with a novel disruption management strategy of on-site installation flexibility that can benefit their organisation in several ways. It helps to avoid project delay. This means costly delay penalties are eliminated or reduced and any tied-up resources are freed to work on other projects. Furthermore, it alleviates the reliance on storing modules as a disruption management strategy. Finally, enabling on-site installation flexibility means that projects are more likely to be completed on time. This could give a competitive advantage to modular off-site construction companies by offering developers greater confidence that their projects will start paying back on their investment on schedule.
3. The implementation roadmaps devised in Chapter 4 guide practitioners through the set of steps they would need to undertake to enable on-site installation flexibility. They help practitioners gauge whether it is feasible for their company to enable each type of on-site installation flexibility. The challenges as a result of the interdependencies between the decisions made for each enabler were highlighted as well as the cost-efficiencies that could be achieved by enabling more than one type of installation flexibility in parallel.

4. An approach to help practitioners determine the level of on-site installation flexibility that they should implement when weighed against alternative disruption management options is provided in Chapter 5.
5. This thesis provides practical insight into the behaviour and limitations of each type of on-site installation flexibility as well as different combinations thereof in Chapter 6, Case Study A.

7.4 Limitations of the research

There are several limitations in the research methods chosen and the findings reported in this thesis.

Limitations of the exploratory study of the main operational disruption and management strategies:

- **The case study company participants operated predominantly in the UK**: Modular off-site construction companies in other regions of the world are likely to be faced with different disruptions and therefore may be using different disruption management strategies to those reported in this study. For instance, weather conditions, government regulations, and space limitations differ from region to region.
- **Most of the case study companies produced module structures from steel and concrete:** In this study, four out of the five case study companies produced modules from steel and concrete and only one from timber. Hence, the findings may be biased towards the operational disruptions and disruption management strategies used by the former.
- **Most of the case study companies did not act as a main project contractor:** In this study, only Company A worked as a main contractor on projects. Hence the disruptions and the management strategies used by such companies may be under-represented in the findings.
- **Some participants appeared reluctant to admit that they faced disruptions:** For instance, Company D stated that they did not have any problems that they could not cope with and only faced a very limited set of disruptions. Hence, the findings might not accurately represent the true state of disruptions and disruption management in the modular off-site construction industry. Nevertheless, this reluctance to share data was partially mitigated against by using a multi-case and workshop methodology.
- **Participants may be experiencing disruptions and using disruption management strategies that may not have come to mind during discussions**: Because the primary data was information shared through interviews with participants from the five case study companies

and workshop, it can be expected that participants may not have recalled in the moment all their disruptions and disruption management strategies. That said, this permitted the study only to report the main disruptions and strategies that were at the forefront of their minds.

- **The study does not quantify the severity or occurrences of the disruptions:** Most of the companies did not have records of the likelihood that they faced a given disruption nor of the impact that each had caused.

Limitations of the study on enabling on-site installation flexibility:

- **The participants of the workshop organised to identify the enablers and their interdependencies were from a single company based in the UK**: Companies in different regions may have additional or fewer enablers required for each type of on-site installation flexibility. Hence, the findings risk not being transferable to other modular off-site construction companies.
- **The amount of effort required to achieve each enabler is not considered:** Interpretive Structural Modelling does not give any indication as to how much effort is required on behalf of practitioners to achieve each enabler. Hence, even though a given flexibility type requires more enablers, it may not necessarily require more effort to implement.
- **The interdependencies between the enablers are not statistically validated:** The limitation of using Interpretive Structural Modelling is that the interdependencies between the identified enablers are not statistically validated.
- **Combining more than one type of on-site installation flexibility would require its own unique roadmap:** Implementation roadmaps created in this study are for individual on-site installation flexibility. Should a company desire to implement a specific combination of the different types of on-site installation flexibility, roadmaps would have to be devised to achieve this. Additional relationships between enablers may have to be captured to factor in the relationships between the enablers that were not common between the two or more types of flexibility in a combination. However, many of the relationships between the identified enablers have already been captured and may be re-used.

Limitations of the approach and in the evaluation of the behaviour of the system enabled by on-site installation flexibility:

- **The benefits of on-site installation flexibility may have been overestimated:**
    - The DES model is a simplification of a real system. It did not consider the full range of disruptions reported in Chapter 3, and instead focussed particularly on the module

delays caused by Type 1 disruptions. What is more, the model did not factor in the risk of new disruptions happening as a result of using on-site installation flexibility, such as the added complexity in changing the nominal module and slot installation sequences that may lead to errors during the installation. In addition, the likelihood a module required re-work was assumed to be equal across all module types. In reality, certain module types may be more prone to delays owing to the fact that some are more complex (e.g. those with a lot of MEP systems integrated). Finally, additional limitations on the level of on-site installation flexibility were not factored in. For instance, full lateral sequence flexibility may not be achievable for certain companies, but they may be able to handle partial lateral sequence flexibility whereby a module can be installed so long as it is fastened to a core or to a module that is in turn attached to a core.

  - The DES model and Integer Linear Program rely on data such as transport time, disruption likelihood, and costs that are unique to a project and may only be obtained after the project has commenced. Hence expert estimates for the data must be used for modelling purposes and this may lead to unreliable results until more experience with the system is accumulated.

- **The benefits of on-site installation flexibility may have been underestimated:**
  - In the DES model, the factory production line was assumed never to be halted as infinite module storage was available (either permanent or emergency). In reality, storage space is limited and securing emergency module storage space at short notice is not always possible. Hence, the factory may be required to halt production until storage space becomes available. Experts stated that this has been costly to them in the past. On-site installation flexibility would help prevent this from happening by reducing the maximum number of modules that need to be stored at any given time. What is more, the Integer Linear Program does not factor in monetary gains as a result of on-site installation flexibility reducing the total floor completion delay.
  - Currently, companies produce modules according to the nominal on-site slot installation sequence. This is because companies do not want to store completed modules while the next module to be installed is still being produced. Enabling on-site installation flexibility would mean that the installation sequence is more flexible. One of the benefits of this is that the factory production may now be sequenced to optimise for production efficiency instead. This gain in efficiency could allow for the

company to produce more modules. The findings from the DES model do not reflect this gain.

- For slot assignment flexibilities, the requirement that modules be of a similar finish and even structure may mean that a range of components must be standardised across the project. This may in turn make the factory more efficient, less error prone, and more cost effective.
- The DES model attempted to adhere as closely as possible to the nominal slot installation sequence by installing the module which was produced earliest. However, it may be that with on-site installation flexibility, a more optimal slot installation sequence could exist that would achieve a better system performance.

7.5 Recommendations for future research

Areas for future research on disruptions and disruption management strategies for modular off-site construction include:

- **Quantifying the occurrence and severity of disruptions in modular off-site construction:** Such a study would help identify which disruptions are most detrimental to the industry and would benefit the most from further research in how to manage them.
- **Research into the extent that the disruptions and disruption management strategies identified in the UK can be generalised across the industry and the world:** The research conducted in Chapter 3 should be undertaken in other regions of the world where the disruptions and their corresponding disruption management strategies may not be the same. In addition, it should be investigated whether the following have any bearing on the findings: i) the type of material the companies use to produce modules, and ii) their status as main or subsidiary contractor on projects.

Future research on enabling on-site installation flexibility:

- **Investigation of the practicality and cost of enabling on-site installation flexibility:** Research is needed in many areas related to enabling on-site installation flexibility. For example, the engineering challenges of designing a building that can use on-site installation flexibility but still maintain structural integrity and adhere to the strict tolerance requirements. Another area could be how to modify current Building Information Modelling (BIM) systems to integrate real-time updates in module and slot installation sequences. A study of how to manage site operations with real-time updates would also be of benefit.

- **Generalisation of the findings in terms of the enablers of on-site installation flexibility and their interdependencies:** The workshop conducted in Chapter 4 could be replicated with other modular off-site construction companies to ensure that the findings regarding the enablers and interdependencies are not company specific.
- **Statistical study validating the interdependencies between enablers:** Other methods such as Structural Equation Modelling could be used to verify statistically the interdependencies between the enablers.

Suggestions for more general on-site installation flexibility research:

- **Exploration of the applicability of on-site installation flexibility to other types of off-site construction:** Other types of off-site construction (e.g, panelised rather than modular) may benefit from on-site installation flexibility. The enablers required and the interdependencies between them may differ from modular off-site construction so additional research is required to tailor this strategy to different types of off-site construction. Furthermore, different types of off-site construction may be faced with a different range of disruptions for which the effectiveness of on-site installation flexibility may differ. Hence, further research would be required in evaluating the behaviour of other off-site construction systems enabled by on-site installation flexibility.
- **Analysis of the benefits of partial implementation of the different on-site installation flexibility types:** In this research, complete flexibility for each type of on-site installation flexibility was investigated. However, in some cases, each on-site installation flexibility type may only be partially implementable. For instance, for vertical sequence flexibility, it may only be possible to install modules on two floors at the same time, rather than having no restrictions as was assumed here. In this thesis, lateral sequence flexibility assumed that slots could be filled in an unrestricted manner on a given floor. However, it may be that modules must either be attached to a core or to another module or modules that are themselves attached to a core. The benefits of this may be that more restricted versions of on-site installation flexibility are more feasible and cheaper to implement and hence a better performance could be achieved.
- **Research into the benefits of on-site installation flexibility in improving factory production efficiency:** Research into the extent to which on-site installation flexibility would allow the factory production sequence to be altered to improve production efficiency would be of

interest. Developing a model to determine the optimal module production and slot installation sequence concurrently would help to answer this.

- **Investigation of whether there is a more resilient nominal slot installation sequence that allows for more effective use of on-site installation flexibility:** For example, if a certain module type is more prone to disruption, it may be better to install such modules earlier in the sequence to give the opportunity for on-site installation flexibility to mitigate any effect of their disruption before the rest of the floor is completed. As a second example, two nominal slot installation sequences may have the same project completion time, but one may reduce the module dwell time or maximum number of modules in the buffer more than the other. Developing a multi-objective optimisation may be of value to investigate this.
- **Equation or flowchart-based formulations describing the behaviour of the different on-site installation flexibility types:** Section 4.3 described the behaviour of the different on-site installation flexibilities by use of example scenarios. It would be of value to capture this behaviour mathematically or through flow charts that could subsequently be used as a starting point to create analytical models.
- **Generalisation of the findings to other building layouts and module compositions**: Two representative case studies were modelled from which a series of propositions were developed. Some of the propositions that concerned the relative performance of different flexibility combinations would merit further investigation with different building layouts and module type compositions to see if they still hold true. Notably, the fact that enabling additional flexibilities on top of lateral and vertical sequence flexibility is of little benefit in terms of improving the mean percentage reduction in delay, total module dwell time in the buffer, and maximum number of modules in the buffer.

Future research on modelling the behaviour of systems enabled by on-site installation flexibility:

- **Extension of the Discrete Event Simulation model:** The model could consider a greater range of disruptions including those downstream of the factory such as transport damage and weather disruptions. Moreover, it could also be further extended to consider a factory producing modules for multiple sites at the same time. In addition, different probabilities of module disruption depending on the module type could be incorporated.

This study began by identifying the main operational disruptions and disruption management strategies used in modular off-site construction. Based on their shortcomings, a novel, flexibility-based, disruption management strategy of on-site installation flexibility was proposed and investigated. Addressing the suggestions for future research above, a more complete insight into disruptions and disruption management strategies used by modular off-site construction companies could be obtained. In addition, greater confidence in whether on-site installation flexibility is a viable disruption management strategy for the modular off-site construction industry could be achieved.

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Appendix A

Appendix A pertains to Chapter 3.

A.1 Exploratory case study data source selection

Based on the recommendations from (Yin, 2014), three types of data sources were used to collect evidence:

1. **Interviews**: these allow the capture of detailed insight and explanations from industry experts. This is particularly useful when addressing the four objectives of Chapter 3. Both *joint interviews*, where there are two interviewees (Arksey and Knight, 1999), and *group interviews*, where there are more than two but fewer than six participants at which point it becomes a focus group (Nyumba *et al.*, 2018) were carried out. The former were used for a number of reasons (Arksey and Knight, 1999): i) establishing a rapport and confidence is easier, ii) it provides two perspectives that may agree or disagree, thereby enriching the findings, and iii) it avoids the bias of a single interviewee. The latter was used for one of the case studies in which a more in-depth analysis of the company's operations was conducted to complement the study by furthering the understanding of the context of a modular off-site construction company's operations.

   The interviews were conducted with senior members of the organisations as they are most likely to have a good overview of the main operational disruptions and management strategies. Steps were taken by the moderator so that all participants had a chance to speak to mitigate the risk of one interviewee dominating the conversation.

2. **Direct observations**: guided tours of the companies' factories were another source of evidence that was used to obtain further live insight into the industrial context. Not only did the tours allow to see the key elements of the factory operations but also to talk to factory workers who dealt with disruptions at first hand and see some of the disruption management techniques being used in practice.

3. **Archival records**: such as publicly disclosed financial statements, documentation such as news articles and internal production data of the companies were also used as additional evidence given the factual nature of the information that they provide.

In all, a wide variety of sources was used to enhance *data triangulation*.

A.2 Case study and workshop participant selection criteria

The selection criteria used to choose the five case study companies are detailed and justified next:

1. The company must be classed as a Medium or Large Business according to the classification of the European Commission (European Commission, 2015). This was included to mitigate the risk that the operational disruptions and the management strategies uncovered during the interviews were as a result of a company's lack of experience or know-how.
2. The company must own and operate an off-site construction factory where most of a module's assembly is done. This was included to ensure that a broad range of operational disruptions was captured.
3. The company must work on projects either as a main contractor or tier one subcontractor. This ensured that they were familiar with as many operational disruptions as possible.
4. The company must produce modules for a range of different end uses (e.g. commercial, residential, hospitality) so that the disruptions were not restricted to products destined for a single market as this might have biased the findings.
5. The company must produce modules that are either primarily made of timber or consist of a steel frame & concrete floor. Most modular builds use these materials and hence this ensured that the findings were broadly relevant across the modular off-site construction industry.
6. The company must provide access to senior decision-making staff who oversee the daily operations of their modular off-site construction projects. This ensured that they were familiar with the main operational disruptions and the respective disruption management strategies that their companies used.
7. The companies should be based in the UK to minimise the time and cost of the research whilst maximising returns.

The selection criteria used to invite the participants to the workshop are detailed and justified next:

1. The participants had either to be:
    a. a representative of a company matching the criteria for those selected in the case-studies and for the same reasons, or
    b. someone who had worked on, or had been involved in some capacity in, tasks linked to a modular off-site construction project of a company matching the criteria for those selected in the case-studies and for the same reasons.
2. The participants of the workshop did not need to be decision-makers on modular off-site construction projects but could have been, for instance, consultants or advisors – which contrasted with the requirement for the interviewees of the case studies. This was to obtain a broader range of insights to enrich the findings as participants such as these were likely to have worked on a greater breadth of projects.

A.3 Details of main operational disruptions

Sixteen kinds of operational disruptions were identified during this study. This section describes each one, citing examples provided by the participants.

A.3.1 Disruptions inbound to the factory

1. **Material not delivered on time to factory:** As show in Table 3.6, four of the five case study companies as well as the workshop participants mentioned that material not being delivered on time to the factory was a common issue. In general, the interviews revealed that the companies had only a limited idea of when material was going to be delivered. This information was typically obtained through regular updates with suppliers on the phone or in person. Hence there is a marked degree of uncertainty at present in this part of their operation. Company C explained that one of the reasons for material not being delivered on time is that the off-site supply chain is not accustomed to working with a just in time mentality and does not understand how critical this is to allow their factory to operate effectively. The lack of maturity of the supply chain was also echoed in the industrial workshop.

Companies A and C reported that on average their projects had between 5-20% of bespoke components for their modules. Such components were usually used for the visible customisation that the end user would see such as the kitchen hobs, mounting brackets for televisions, and tiles. Experts from the workshop also mentioned that bespoke project-specific items were the most likely to cause disruptions given that it is hard to source them elsewhere from a second supplier. Furthermore, given the one-off demand for bespoke items, it was reported that it was difficult to build meaningful relationships with the suppliers of such parts. Company E reported that on average about 15% of their modules face a shortage of parts during any given week as a result of this type of disruption.

2. **Incorrect material delivered to factory**: The workshop participants and three of the case study companies reported that incorrect material being supplied to the factory was a common disruption. Such problems were mostly attributed to human error in interpreting the orders or in certain circumstances because the wrong material was ordered from a supplier. For example, a client of Company A changed its mind during the initial discussions for the colour of some boarding. The company failed to relay this change to the supplier before production commenced and consequently a disruption occurred.

A.3.2 Disruptions in the factory

3. **Component damage during production**: Given the labour-intensive work in the factory, component damage often occurred because of operator error. This could cause significant delays if the components were bespoke for the project. For instance, in some cases it was reported that windows took up to 14 weeks to be re-ordered and tiles up to 20 weeks.
4. **Design change request during production**: Most companies enforce a design freeze several weeks ahead of production whereby the design of the modules is signed off by the clients, material sourcing officially commences, and the production slot is booked in the factory. For instance, for Company B this period is 4-6 weeks prior to the start of production and for Company C it is 22 weeks prior to the on-site installation date. Despite this, clients sometimes change their minds and this causes disruptions. Company B gave a specific example of a budget hotel project where after the first few modules were produced, the client decided the interior finish no longer suited their business needs and asked for changes to be made on all the modules. Company E, which primarily produces residential products, also provided

examples where clients inspected progress and realised certain aspects were not as they had envisaged and consequently requested modifications.

5. **Lack of skilled labour**: This is an issue for the modular off-site construction companies that were interviewed. Company B said that they invested in training their workforce and apprentices in the hope that they would remain with the company for the long-term, but they often would leave the company during the summer months, when they would work as private contractors and earn a better wage. Construction workers habitually work on a series of short-term jobs and it is difficult to change their attitudes. Consequent labour shortages affected the ability of the companies to meet their production deadlines.

A.3.3 Disruptions between the factory and the construction site

6. **Damage during storage**: Company E and the workshop participants reported that exposure to the elements during storage occasionally led to water seeping through the packaging of the modules and causing damage. Another source of damage during storage is vandalism of the modules.
7. **Damage during transport**: Collisions and heavy braking during transport reportedly lead to module distortion and damage because of the momentary shocks to which the modules are subjected. For example, Company A reported one instance where a crash resulted in a module being completely written off. Similarly to when in storage, the modules are exposed to the elements when being transported and are vulnerable to water damage.

8–11. **Other transport disruptions**: Traffic congestion and unexpected obstacles on the route are a challenge for the companies that frequently have projects in dense urban environments such as London. The length of the modules makes sharp turns to circumvent obstacles difficult. Closed roads can create significant holdbacks if no alternative wide enough route is easily accessible. Lack of adequate haulage and escort vehicles also disrupted the transportation operations of several of the companies. Escort vehicles are required in the UK for abnormal loads of the size of the modules.

12. **Difficulties in unloading modules**: Workshop participants also mentioned difficulties occurring when unloading the modules at storage locations or at the site because they are very sensitive to shocks. Moreover, some companies seek to minimise the number of lifts a module must endure to minimise the risk of distortion.

A.3.4 Disruptions at the construction site

13. **High-wind conditions:** If winds exceed a certain threshold at the construction site, the cranes used to hoist the modules are not allowed to operate. One of the participant companies of the workshop noted that mobile cranes cease to operate at gusts over 21mph, crawler cranes 31mph, and tower cranes 38mph as they cannot prevent the large modules from swinging erratically. Furthermore, the more storeys a building has, the greater the wind speed at higher elevations and hence the greater the chance of high-wind disruptions.
14. **Foundations not completed on time**: Delays in completing the foundations owing to poor co-ordination, mismanagement or errors on site were also reported by many of the participants. Company B gave the example of one project where the foundations were delayed for six months.

15–16. **Crane unavailability and breakdowns**: The unavailability of cranes was another cause of disruptions to modular off-site construction projects. There is a very limited number of cranes that can hoist loads as heavy as the modules, as is the case for Company C's that each weigh between 25 and 27 tonnes. Another company stated that there were only six cranes in the UK capable of lifting its modules. Company C also noted that such cranes are prone to breaking down.

A.4 Details of the disruption management strategies

Nine disruption management strategies were reported by the participants. It is explained below how each one is used for disruption management, citing examples provided by the participants:

1. **Re-work module to remedy issue:** Re-work was cited as one of the main means of responding to disruptions where additional work has to be undertaken on a module before it can be installed at the construction site. It allows for corrective work on modules rather than scrapping partially completed assemblies thereby avoiding an otherwise much longer delay and higher costs. Some companies such as Company B had dedicated re-work stations that occupied space in the factory. Company A usually quarantined modules on the production line whenever possible to conduct re-work. Company D and Company E adopt another approach by carrying out the re-work in the storage areas.

2. **Storage of module pending installation:** Table 3.6 shows that investing in a module storage area was the most used strategy to manage disruptions. Indeed, all five companies interviewed used this strategy, and it was cited 30 times as a disruption management strategy across the 16 disruptions encountered. The companies use this strategy to keep their production lines running by allowing completed modules to leave the line so that the next modules can be started. Companies invest in both permanent and emergency storage, with the costlier emergency storage space only being used when they run out of permanent storage because of a build-up of modules in long-lasting disruptions.
3. **Send module to site partially finished:** Several of the companies reported that they sometimes sent modules partially finished from the factory to the construction site. This strategy is unique to the modular off-site construction industry and has not been reported previously. Consider the case where a part (e.g. a heater) does not arrive in time to be fitted into a product (e.g. a module) on a production line. In many industries, such as the automotive industry, the product must be taken offline and wait for the part to arrive before being fitted into the product. However, in the off-site construction industry, the part can be sent on and fitted downstream at the construction site. Companies A, B, and E advocated its use provided that the lack of the component did not impede follow-on work on the module from being completed in the factory and that the resulting partially completed module was weatherproof. If so, the businesses would decide to re-schedule the unfinished work for completion at the site. The benefits of this are that the installation process at the site is not halted and the high costs of the crane and labour on site are not wasted, and no delivery delay penalty is incurred.
4. **Overtime to make up for lost time**: Overtime was used to make up the lost time or additional work that may have been required because of disruptions inbound to the factory or component damage.
5. **Substitute component with similar part**: Should there be a delay in supplying a component or damage to a component during production, some of the companies substitute the affected component with another similar one.
6. **Safety stock of parts**: Holding a safety stock of components ahead of when they are needed to avoid the risk of running out of stock. For example, Company B aims to hold 50-60% of the Bill of Materials of a module two weeks prior to commencing production.
7. **Vertical integration**: The lack of haulage and escort vehicle availability led Company B to bring its transport operations in-house rather than subcontracting them to a haulage company. Indeed, Company B invested in five of its own haulage vehicles and several escort vehicles, thereby vertically integrating this part of their project operations.

8. **Risk management built into contract:** Incorporating risk management measures in contracts acts as a disruption management strategy. For example, Company B said that in certain circumstances they have a shared cost and benefit agreement whereby stakeholders share the cost of using a given disruption management strategy which would greatly help the overall project but which would otherwise have been too costly for the company alone to bear.
9. **Produce more than one project at a time:** Company A uses a disruption management strategy in which it actively tries to produce modules for more than one project at any given time. They argue that this helps prevent all work in the factory from coming to a halt if there is a disruption that affects all modules of one particular project.

Appendix B

Appendix B pertains to Chapter 4.

B.1 Methodology details

B.1.1 Evaluation and selection of quantitative methods

In this section, methods to achieve Chapter 4's objectives 3 and 4 were identified and evaluated. Six criteria were defined to select the most appropriate method. The chosen method had to be:

Criterion 1: Capable of capturing and analysing uni-directional (e.g. the enablement of Enabler A influences that of Enabler B) and bi-directional (e.g. Enablers A and B influence the enablement of each other) interdependencies between enablers. This criterion is needed to capture accurately the requirements of enabling each type of on-site installation flexibility.

Criterion 2: Capable of capturing and analysing complex indirect relationships between enablers. For example, if enabling Enabler B is directly dependent on Enabler A being enabled and Enabler C is dependent on Enabler B, then enabling Enabler C also depends on Enabler A being enabled. This criterion is also needed to capture accurately the requirements of enabling each type of on-site installation flexibility.

Criterion 3: Capable of analysing and providing insight into the degree of influence of each enabler on others. A better understanding of the interdependencies can consequently be gained.

Criterion 4: Capable of creating a hierarchy between enablers to form an implementation roadmap.

Criterion 5: Adequate for exploring new fields of research that are not yet established.

Criterion 6: Easily understood by practitioners so that they can contribute to, evaluate, and trust the outputs.

The *Analytical Network Process* (ANP) can analyse interdependencies between enablers but does not output an implementation roadmap (Saaty, 2006). It has been said to be too complex for most practitioners to understand and trust (Mangla *et al.*, 2018). *Structural Equation Modelling* (SEM) is capable of capturing uni-directional and indirect interdependencies but not bi-directional ones (Kaplan, 2009). It is not adequate for ill-defined fields of research (D Vivek, Banwet and Shankar, 2008) and also requires a large number of data points to be collected (Mangla *et al.*, 2018). The *Decision Making Trial and Evaluation Laboratory* (DEMATEL) method takes into consideration the interdependencies between the enablers by asking experts to quantify their influence on the others on a scale of 0 to 3 (Shieh, Wu and Huang, 2010). It can determine the strength of the overall effect each enabler has on enabling on-site installation flexibility as well as whether they are primarily influenced by other enablers or vice-versa.

Similarly, *Impact Matrix Cross-Reference Multiplication Applied to a Classification* (MICMAC) can analyse the driving power and dependence power of enablers of on-site installation flexibility (Kapse *et al.*, 2018). Unlike DEMATEL, practitioners are simply asked whether an enabler influences another as a binary decision. This is preferable given this area of research is still in its infancy and therefore it is hard to gauge each individual enabler's influence on another. MICMAC then classifies enablers into one of four categories (Raj, Shankar and Suhaib, 2008) (Autonomous, Independent, Dependent, and Linkage) that provide an easily understandable way for practitioners to comprehend the interdependencies and their degree of influence. Enablers with high driving power should be the initial point of focus as they will influence the implementation of other enablers. What is more, MICMAC is suited to this application as it has been proven to aid organisations to classify enablers needed to turn strategic and tactical decisions into reality in comparable systems (Raval, Kant and Shankar, 2018).

Interpretive Structural Modelling (ISM) has been used in the past to construct implementation roadmaps (Mehta, Verma and Seth, 2013; Ahuja, Sawhney and Arif, 2017). The benefit of the roadmap being formulated from ISM is that it gives practitioners a clear sequence to follow to implement the enablers. Moreover, it is understandable to users from a wide range of interdisciplinary groups (D Vivek, Banwet and Shankar, 2008). It can also incorporate a large number of components of complex systems such as those of off-site construction (D Vivek, Banwet and Shankar, 2008). Furthermore, ISM has previously been used to model enablers which shows it is an established method of choice for this type of research (Raj, Shankar and Suhaib, 2008; Mangla, Madaan and Chan, 2013; Purohit *et al.*, 2016; Raval, Kant and Shankar, 2018). In addition, ISM can analyse complex problems, such as how to enable on-site installation flexibility, and provide clear solutions (Mangla, Madaan and Chan, 2013). An additional point of interest is that some of the preliminary steps of applying the ISM method are common with the MICMAC method and as such have frequently been conducted together (Purohit *et al.*, 2016; Ahuja, Sawhney and Arif, 2017). However, the focus of ISM is not to provide insight into the degree of influence each enabler has on others, unlike DEMATEL and MICMAC (Kapse *et al.*, 2018).

To summarise, Table B.1 shows that no single method was found to fulfil all the criteria. Consequently, ISM combined with a MICMAC approach were chosen as they most closely met and collectively fulfilled the criteria.

Table B.1: Summary of how each method fulfils the various criteria. Green = Yes; Red = No.

#	Criterion	ANP	SEM	DEMATEL	MICMAC	ISM
1	Capture and analyse uni- and bi-directional interdependencies	Yes	No	Yes	Yes	Yes
2	Capture and analyse complex indirect relationships between enablers	Yes	Yes	Yes	Yes	Yes
3	Analyse and provide insight into the degree of influence each enabler has on others	Yes	Yes	Yes	Yes	No
4	Create a hierarchy between enablers to form an implementation roadmap	Yes	No	No	No	Yes
5	Adequate for exploring new fields of research that are not yet established	Yes	No	No	Yes	Yes
6	Easily understood by practitioners	No	Yes	Yes	Yes	Yes

B.1.2 Interpretive Structural Modelling

Based on the procedure described in (Chirra and Kumar, 2018), the following steps were conducted in the ISM analysis:

Step 1: ***Identify the enablers:*** for each on-site installation flexibility type, the enablers were generated by the experts by brainstorming, following (Raval, Kant and Shankar, 2018). The enablers were subsequently categorised into groups of common themes. It was decided to consider the enablers from the viewpoint of a modular off-site construction company that produced modules that are different in terms of interior and exterior finish. The reason being that fewer enablers would be required if all modules were identical. Hence, this view maximises the relevance of the research findings by covering the "worst case" in which the most changes would be required to enable each flexibility type.

Step 2: ***Discuss interdependencies between enablers:*** the interdependencies between each enabler and the practicalities of unlocking them were identified through discussions with the experts.

Step 3: ***Develop the Structural Self Interaction Matrix (SSIM):*** based on the discussions in Step 2, a matrix of pairwise comparisons of the enablers was completed by entering a:

- "V" where enabler i will influence the enablement of enabler j.
- "A" where enabler j will influence the enablement of enabler i.
- "X" where enabler i and j will influence the enablement of each other.
- "O" where enabler i and enabler j have no relationship with each other.

Step 4: ***Create the Initial Reachability Matrix (IRM):*** the "V", "A", "X", "O" symbols were substituted with binary digits following the rules in (Dubey, Gunasekaran and Chakrabarty, 2017):

- If any entry in the SSIM is equal to "V", then element (i,j) of the IRM is set to 1 and element (j,i) is set to 0;
- If any entry in the SSIM is equal to "A", then element (i,j) of the IRM is set to 0 and element (j,i) is set to 1;
- If any entry in the SSIM is equal to "X", then element (i,j) of the IRM is set to 1 and element (j,i) is set to 1;
- If any entry in the SSIM is equal to "O", then element (i,j) of the IRM is set to 0 and element (j,i) is set to 0;

Step 5: ***Create the Final Reachability Matrix (FRM)*****:** the FRM was created by incorporating the ISM concept of transitivity, which states that if element "A" is related to an element "B" and element "B" is related to element "C", then element "A" must also be related to element "C". In doing so relevant elements equal to 0 were replaced with "1*", denoting a transitive link.

Step 6: ***Partition the FRM into different levels:*** the enablers were subsequently partitioned into a hierarchy of levels, in which the enablers in the lowest level are necessary to enable all other enablers. Enablers were partitioned into levels in the following manner:

- The reachability, antecedent, and intersect sets were computed for each enabler:
  - The reachability set of each enabler is composed of all enablers that help achieve it.
  - The antecedent set of each enabler is composed of all enablers that it enables and itself.

- The intersect set of each enabler is the intersect of its reachability set and its antecedent set.

- The enablers for which the reachability set was equal to its intersect set were identified. These enablers were part of the Level “I” set.
- All rows and columns corresponding to any of the enablers which were part of the level “I” set from the FRM were removed.
- The process was repeated until all enablers belong to a level set.

Step 7: ***Draw the digraph:*** The links in the FRM were used to form the digraph and remove those that were transitive.

Step 8: ***Create the ISM:*** The nodes in the digraph were replaced with their respective enablers to create implementation roadmaps.

Step 9: ***Check the model for inconsistencies:*** The ISM was reviewed with the experts and if there were inconsistencies it was necessary to return to step 2 and repeat the process.

For readability, excerpts from the large SSIM and FRM matrices for lateral sequence flexibility are given in Appendix B.3.

B.1.3 MICMAC analysis

Impact Matrix Cross-Reference Multiplication Applied to a Classification (MICMAC) works by first calculating the driving and dependency power of each enabler using the FRM from Step 5 above. The driving power of an enabler was obtained by summing together all elements in the corresponding row for that enabler. The dependency power of an enabler was obtained by summing all elements in the corresponding column for that enabler. The enablers were then classified into one of four categories (autonomous, dependent, linkage, or independent enablers) in accordance with (Raj, Shankar and Suhaib, 2008).

Traditionally, the enablers are then displayed on a scatter plot with driving and dependency power as the axes. The categories to which the enablers belong are defined by the quadrant in which they fall by drawing a vertical and a horizontal line which intersect at the average driving power and dependence power of the enablers, as in (D Vivek, Banwet and Shankar, 2008). However, it was found that given the number of enablers that had the same driving and dependence power, the traditional MICMAC plots were more difficult to visualise because of the overlapping data points. Thus, alternative graphical representations of the classifications obtained from the MICMAC were created. These are presented in Section 4.4.4.

B.1.4 Detailed methodology flowchart

Figure B-1 shows the steps of the ISM and MICMAC methods and their place in the context of the overall methodology. The objectives of Chapter 4 have also been mapped onto the steps that address them.

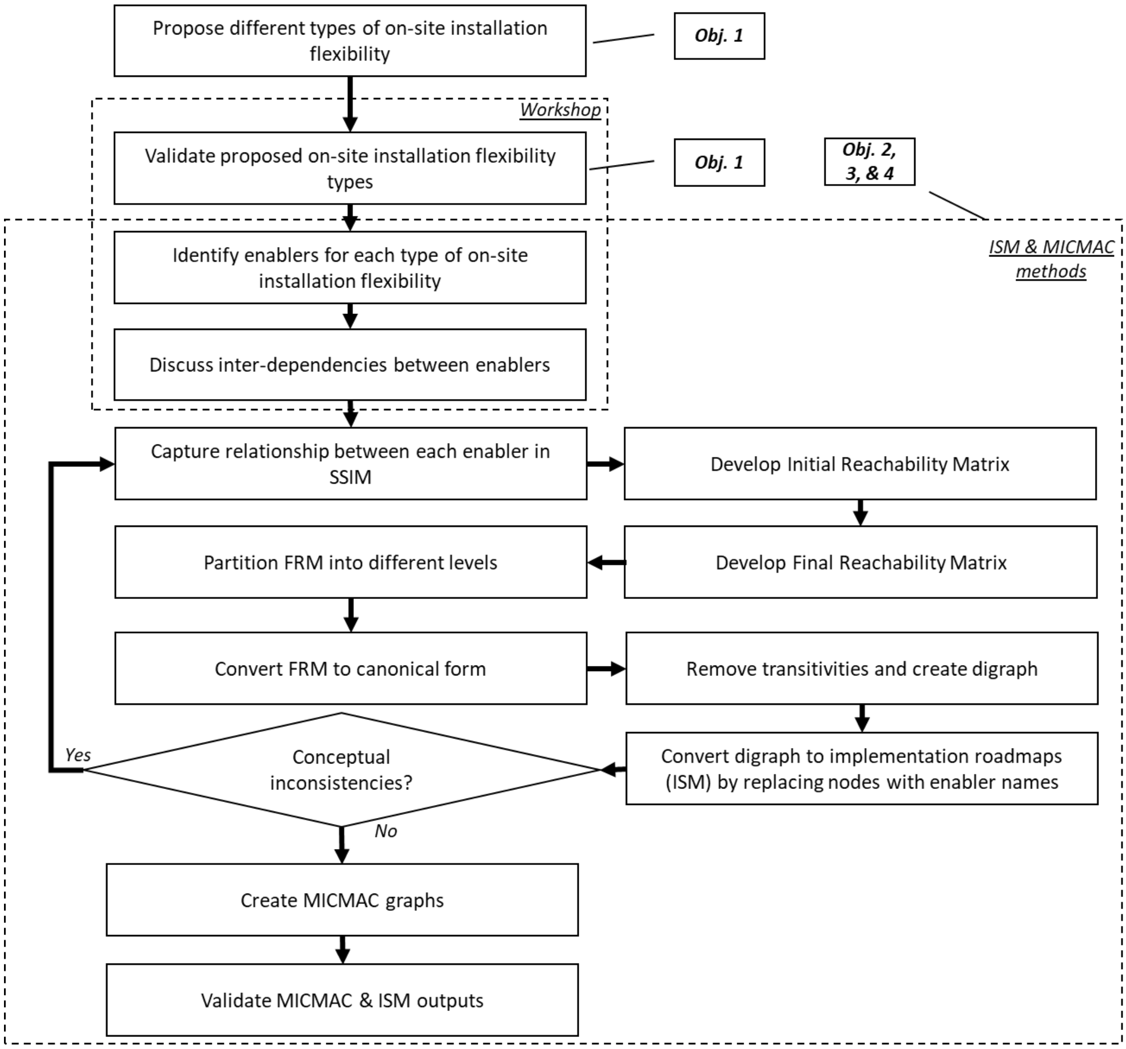

Figure B-1: Detailed methodology for Chapter 4.

B.2 Detailed mapping of enablers identified during the workshop to different types of installation flexibility

Table B.2: Detailed description of enablers and justifications why they are needed for each installation flexibility type. Green = required; Red = not required.

ID	Category	Enabler	Further information	Sequence flexibility		Assignment flexibility	
				Vertical	Lateral	Vertical	Lateral
1	Construction site	Update quality assurance protocol at site	Any changes to the design or the installation process would require the quality assurance protocol to be updated to ensure that the changes do not adversely affect the end product.				
2	Construction site	Availability of additional site personnel to install modules		Additional labour may be required when installing modules on multiple floors at a time (e.g. to ensure safety of those below).			
3	Construction site	Availability of additional site personnel to complete module exterior	Additional labour may be required to complete exterior elements of modules such as the façade or balconies.				

				Sequence flexibility		Assignment flexibility	
ID	Category	Enabler	Further information	Vertical	Lateral	Vertical	Lateral
4	Construction site	Availability of adequate number of craftsmen to finish modules at the site	Additional labour may be required to complete any unfinished modules at the site.			Modules that are part finished at the factory in order to allow for them to be re-assigned would require additional labour at the site to complete them.	Modules that are part finished at the factory in order to allow for them to be re-assigned would require additional labour at the site to complete them.
5	Construction site	Availability of adequate lifting equipment for facilitating movement of material	For example, new lifts to deliver material to the appropriate location in the building and forklifts.			Any material for work that has been postponed from the factory to the construction site would require additional handling equipment.	Any material for work that has been postponed from the factory to the construction site would require additional handling equipment.
6	Construction site	Adequate number of on-site facilities	For example, rest areas, portaloos, and lodgings.			Any additional on-site personnel would require adequate on-site facilities to cater for them.	Any additional on-site personnel would require adequate on-site facilities to cater for them.

ID	Category	Enabler	Further information	Sequence flexibility		Assignment flexibility	
				Vertical	Lateral	Vertical	Lateral
7	Construction site	Availability of adequate tools at the site		Extra tools may be required if modules are being installed on multiple floors at the same time.	Extra tools may be needed to guide the modules into place.	Modules that are part finished at the factory require adequate tools at the site to finish them.	Modules that are part finished at the factory require adequate tools at the site to finish them.
8	Construction site	Create on-site standard operating procedures		If modules are being installed on multiple floors at any given time, changes to the installation methods are required to take into consideration factors such as new risks.	Typically, modules are attached to a core (or a module which has been secured to it). Lateral sequence flexibility would allow modules to forego this requirement. New factors must be incorporated into the existing installation method to ensure that, for example, the tolerances are still respected.		

ID	Category	Enabler	Further information	Sequence flexibility		Assignment flexibility	
				Vertical	Lateral	Vertical	Lateral
9	Construction site	Train site personnel with new methods of installation	This includes any contractors.				
10	Construction site	Jump crane to height capable of reaching all areas of the building from start of project		A crane capable of reaching the highest floor should be at the site from the start to make the most of this flexibility in the case that the only option is to build vertically.			

				Sequence flexibility		Assignment flexibility	
ID	**Category**	**Enabler**	**Further information**	**Vertical**	**Lateral**	**Vertical**	**Lateral**
11	Construction site	Erect temporary works to support the crane		Typically, when a crane is jumped it is progressively secured to the building under construction. As the crane must be at a sufficient height to install modules at the top floor of the building from the beginning, temporary works must be erected to support the crane given that the building does not yet exist.			
12	Construction site	Availability of cranes with adequate span from start of build			A crane (or several cranes) capable of reaching across the entire floor plan of a building is required from the start.		
13	Construction site	Availability of crane with adequate lifting strength				Modules may be heavier as a result of stronger columns.	
14	Construction site	Accurate crane path control	Ability to manoeuvre modules accurately.				

				Sequence flexibility		Assignment flexibility	
ID	**Category**	**Enabler**	**Further information**	**Vertical**	**Lateral**	**Vertical**	**Lateral**
15	Design	Alter module connector design			Module connectors must be adapted to facilitate the requirements of this installation method. For example, additional connectors may be added to the modules given the lack of a nearby core that previously acted as a reference/anchor point.		
16	Design	Re-design load bearing portions of the modules such that they are capable of withstanding lateral loading imbalances		Installing modules out of sequence may induce stresses on the system that may exceed the expected loading limits for a conventional installation sequence.	Installing modules out of sequence may induce stresses on the system that may exceed the expected loading limits for a conventional installation sequence.		

				Sequence flexibility		Assignment flexibility	
ID	Category	Enabler	Further information	Vertical	Lateral	Vertical	Lateral
17	Design	Design "safety walkway" to cover empty slots		Need "safety walkway" to cover gaps between modules on lower floors for the safe passage of labour on upper floors.			
18	Design	Standardise fire compartmentalisation of modules	Modules typically have varying levels of fire compartmentalisation depending on where in a building they are located. As such, modules with identical finish may have a different level of fire-proofing materials applied.			Modules must have a sufficient level of fire compartmentalisation to be re-assigned to any location in a building. Consequently, they must all be re-designed such that they meet this requirement.	Modules must have a sufficient level of fire compartmentalisation to be re-assigned to any location in a building. Consequently, they must all be re-designed such that they meet this requirement.
19	Design	Standardise module structures				The column thickness of modules must be identical to allow re-assignment of modules to different floors.	

ID	Category	Enabler	Further information	Sequence flexibility		Assignment flexibility	
				Vertical	Lateral	Vertical	Lateral
20	Design	Strengthen building foundations				The foundations of the building must be stronger to bear additional weight of the building as a result of module structural changes.	
21	Design	Design floorplan column grid to allow modules to be re-assigned to any appropriate location					
22	Design	Design sufficient spacing between modules		Additional spacing is required between modules to allow a crane to lower modules into gaps between modules, some of which may span more than one floor.	Additional spacing is required between modules to allow a crane to lower modules into gaps between modules.		

				Sequence flexibility		Assignment flexibility	
ID	Category	Enabler	Further information	Vertical	Lateral	Vertical	Lateral
23	Design	Increase the acceptable installation tolerances	Tight installation tolerances are achievable when modules are installed in the traditional sequence. Deviation from the norm would mean that the tolerances are much harder to achieve and consequently the system should be re-designed to relax the requirements.				
24	Design	Standardised balcony fastening mechanism	Create a method by which any variant of balcony can be attached to a module. This way, modules can when necessary have an appropriate balcony attached to them at the site should they be re-assigned to a different slot.				
25	Design	Standardised façade fastening mechanism	Create a method by which any variant of façade can be attached to a module. This way, modules can have an appropriate façade attached to them at the site should they be re-assigned to a different slot.				
26	Design	Design modules such that their load bearing columns can attach anywhere on the floorplan					

ID	Category	Enabler	Further information	Sequence flexibility		Assignment flexibility	
				Vertical	Lateral	Vertical	Lateral
27	Factory	Create off-site standard operating procedures	New standard operating procedures must be developed to take into account any changes in the process outside of the construction site.				
28	Factory	Update manufacturing process		The manufacturing processes would need to be updated based on any changes to the design.	The factory manufacturing process may have to change to adapt to design changes (e.g. additional connectors) or new opportunities for automation.	The factory manufacturing process would have to change to suit design changes (e.g. column thickness alterations). Additionally, any design changes to the exterior (e.g. façade and balconies) would also require changes to the manufacturing process.	The factory manufacturing process would have to change to suit design changes (e.g. changes to the exterior of the module such as the balconies and façade).

				Sequence flexibility		Assignment flexibility	
ID	Category	Enabler	Further information	Vertical	Lateral	Vertical	Lateral
29	Factory	Install adequate factory automation		The factory automation may have to change in line with for instance design changes or new opportunities for automation.	The factory automation may have to change in line with for instance design changes or new opportunities for automation.	The factory automation may have to change to suit design changes (e.g. column thickness changes). Additionally, any design changes to the exterior (e.g. façade and balconies) would also require changes to the automation.	The factory automation may have to change to suit changes to the exterior elements of the modules (e.g. balcony and façade).
30	Factory	Train factory labour	Changes to the factory process would result in the need to retrain the factory labour.				
31	Factory	Availability of factory labour					
32	Factory	Availability of adequate tools at the factory					
33	Factory	Ensure the production line is balanced	Re-assignment of tasks to different workstations.				

				Sequence flexibility		Assignment flexibility	
ID	Category	Enabler	Further information	Vertical	Lateral	Vertical	Lateral
34	Factory	Availability of modules whose interior is finished to a common level at the point they leave the factory	This could be achieved by virtue of the fact that certain modules in a project are the same in terms of finish. Alternatively, it could be achieved by postponing to the construction site some of the finishing work which differentiates modules.			Only modules that are similar in terms of finish can be re-assigned to another slot.	Only modules that are similar in terms of finish can be re-assigned to another slot.
35	Factory	Existence of modules of identical exterior appearance when they leave the factory	This could be achieved by arranging for the exterior of all modules to be identical. Alternatively, operations such as the attachment of the façade and balconies could be postponed to the site.			Modules can only be re-assigned to slots if they have identical exterior appearance.	Modules can only be re-assigned to slots if they have identical exterior appearance.
36	Financial	Funds for construction site changes	Funds are required to enable resources required at the site such as labour.				
37	Financial	Funds for factory changes	Funds are required to enable resources required at the factory such as automation.				
38	Financial	Funds for module specification changes	Funds are required to enable resources required for design changes.				
39	IT Infrastructure	Real time site installation sequence and module slot assignment updates	The construction site must be made aware in a timely manner when the installation sequence is altered owing to a disruption.				

				Sequence flexibility		Assignment flexibility	
ID	**Category**	**Enabler**	**Further information**	**Vertical**	**Lateral**	**Vertical**	**Lateral**
40	IT Infrastructure	Adequate IT infrastructure	The IT system must be updated to be capable of accommodating the new requirements of the system to enable on-site installation flexibility.				
41	IT Infrastructure	Real time on- and off-site system status monitoring	Real time on- and off-site system status monitoring is necessary to ensure that the benefits of flexibility for responding to disruptions are captured. This is geared towards disruption detection and control of the overall process.				
42	Legal	Update building regulations pack	Any changes to the building must be noted and submitted to the building authority in the final as-built documents. Re-assigning a module would count as such a change and hence an update is required.				
43	Legal	Acquire relevant building standard certifications	Certifications must be applied for again for changes in design and process.				

ID	Category	Enabler	Further information	Sequence flexibility		Assignment flexibility	
				Vertical	Lateral	Vertical	Lateral
44	Legal	Adequate H&S procedures	New health and safety procedures may be necessary to reflect any changes in the processes. For example, exclusion zones may have to be set up in areas of the building where certain slots have been left empty on the floorplan. Building floor access strategies would also have to be reviewed.				
45	Legal	Permission to build on all areas of the construction site from the start of the project			Often permission to build on portions of the site is granted incrementally by the building authority, If the lateral installation sequence is to be fully flexible then permission to install modules on all areas of the site is required.		
46	Management	Top management support	The support of executives is necessary to bring about changes to an organisation.				

ID	Category	Enabler	Further information	Sequence flexibility: Vertical	Sequence flexibility: Lateral	Assignment flexibility: Vertical	Assignment flexibility: Lateral
47	Management	Effective communication with the site	Good communication with the construction site is necessary to keep it updated with progress and any eventual disruptions so that it can best prepare.				
48	Management	Client agreement	The client's agreement to changes.				
49	Management	Strategic planning	Strategic planning is necessary to successfully enact changes in the organisation and product.				
50	Management	Project management skills	Adequate project management skills are required to plan any changes required in the design or processes required to build the product.				
51	Management	Effective scheduling	Effective scheduling is required to, for instance, react to disruptions and ensure that all components and resources are available when needed.				
52	Management	Performance measurement	Performance measurement is necessary to fine-tune the processes and the design of the product to ensure that flexibility is a success.				
53	Management	Get support from the unions	The support of the unions is necessary for any changes that may impact the working conditions or tasks expected of personnel.				

ID	Category	Enabler	Further information	Sequence flexibility		Assignment flexibility	
				Vertical	Lateral	Vertical	Lateral
54	Supply chain	Set up supply chain logistics for module design changes	Any changes in the design would require changes to the current supply chain both in terms of suppliers and logistics.		New module connectors to facilitate the requirements of this installation method must be sourced.	Need to source stronger columns.	
55	Supply chain	Set up supply chain for "safety walkway" production	The necessary manufacturing and supply chain steps to produce a "safety walkway" need to be set up.				
56	Supply chain	Set up supply chain to ensure appropriate material is delivered to the site	Any work that is postponed at the factory requires the relevant material to be transferred to the site.				

B.3 Excerpts of SSIM and FRM

Table B.3: Excerpt from SSIM of lateral sequence flexibility.

	Update quality assurance protocol at site	Availability of adequate tools at the site	Create on-site standard operating procedures	Train site personnel with new methods of installation	…
Update quality assurance protocol at site		A	A	A	…
Availability of adequate tools at the site			O	V	…
Create on-site standard operating procedures				V	…
Train site personnel with new methods of installation					…
…					

Table B.4: Excerpt from FRM for lateral sequence flexibility.

	Update quality assurance protocol at site	Availability of adequate tools at the site	Create on-site standard operating procedures	Train site personnel with new methods of installation	…
Update quality assurance protocol at site	1	0	0	0	…
Availability of adequate tools at the site	1	1	1*	1	…
Create on-site standard operating procedures	1	1*	1	1	…
Train site personnel with new methods of installation	1	1*	1*	1	…
…	…	…	…	…	…

B.4 Implementation roadmaps

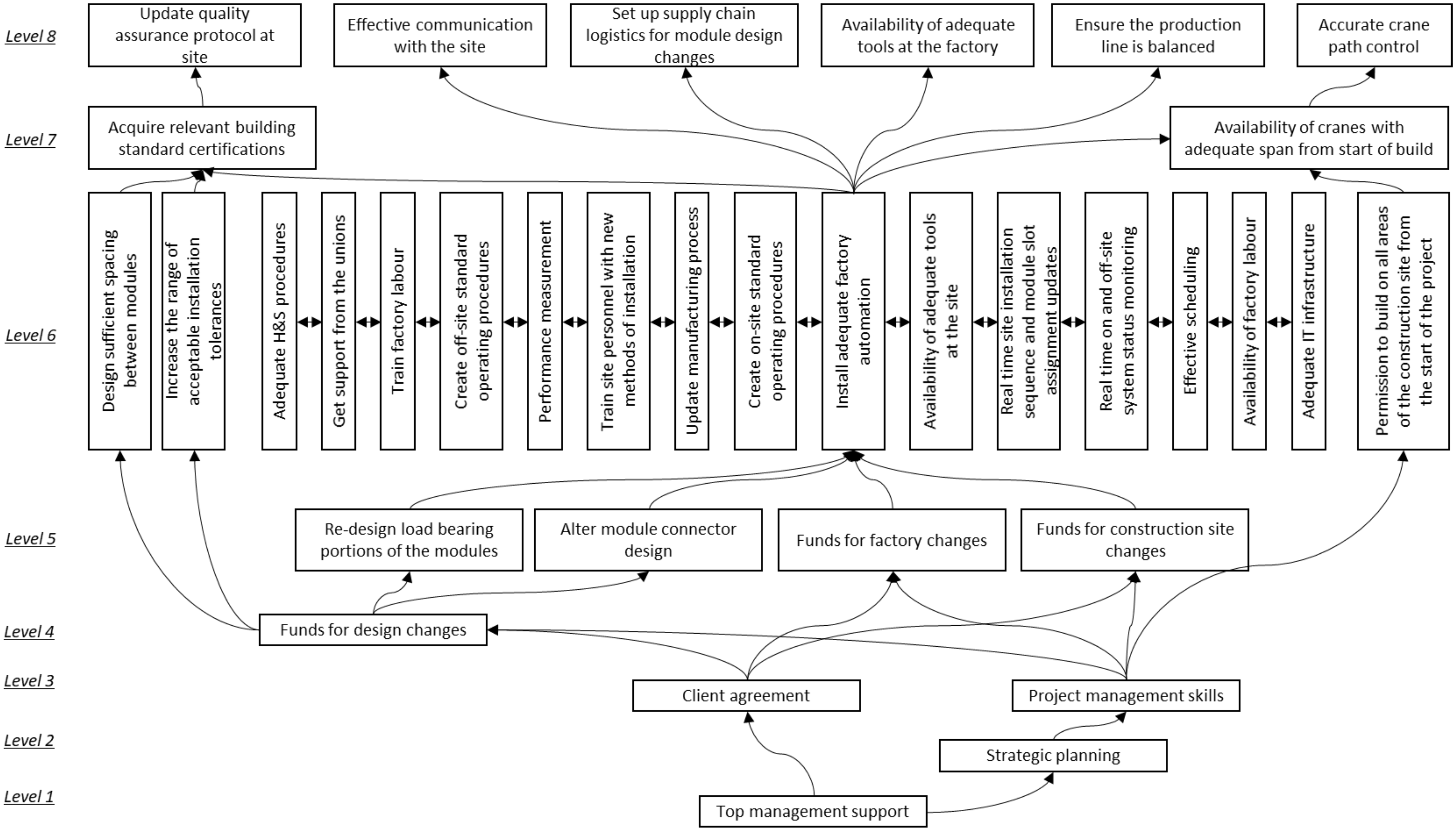

Figure B-2: Implementation roadmap for lateral sequence flexibility.

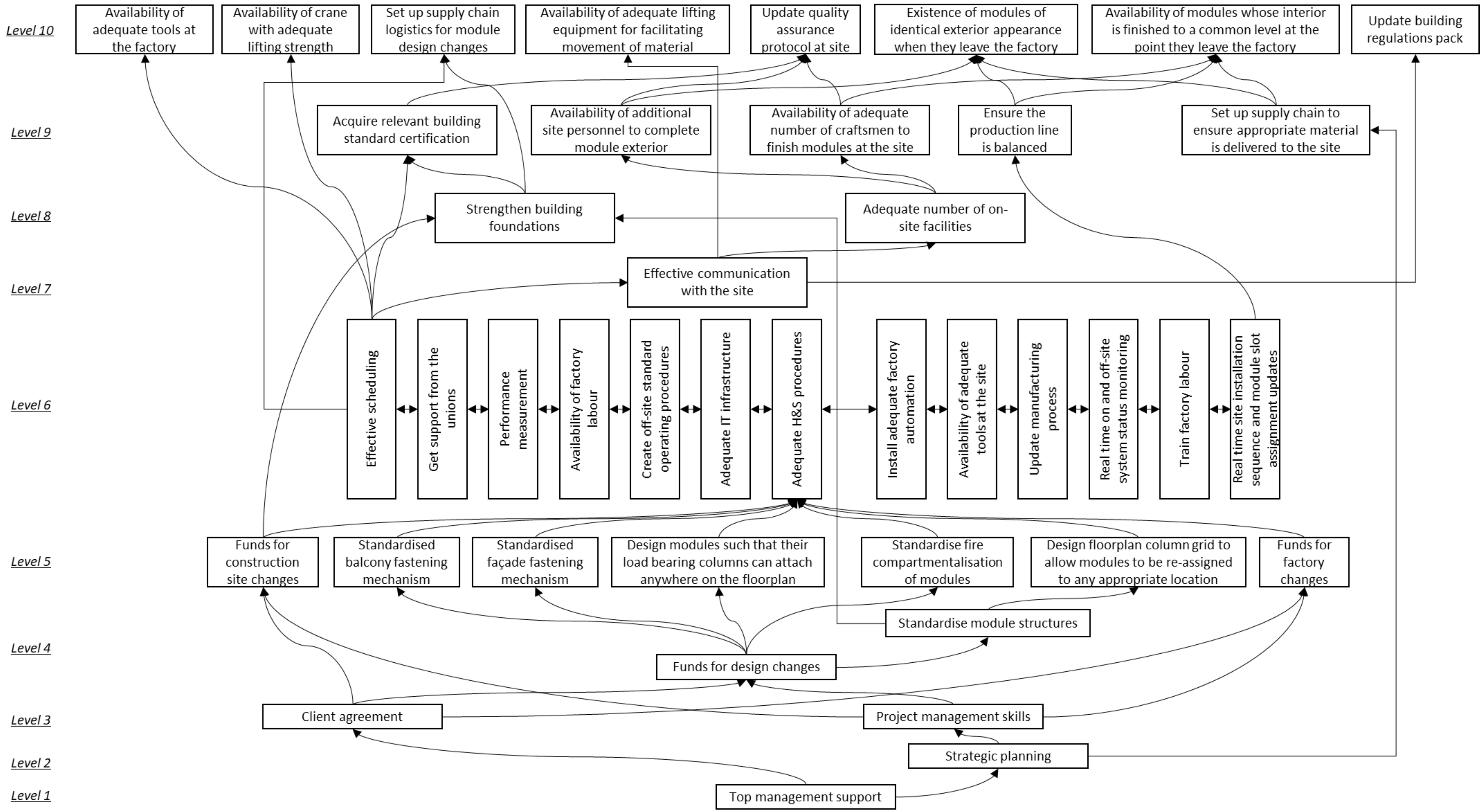

Figure B-3: Implementation roadmap for vertical assignment flexibility.

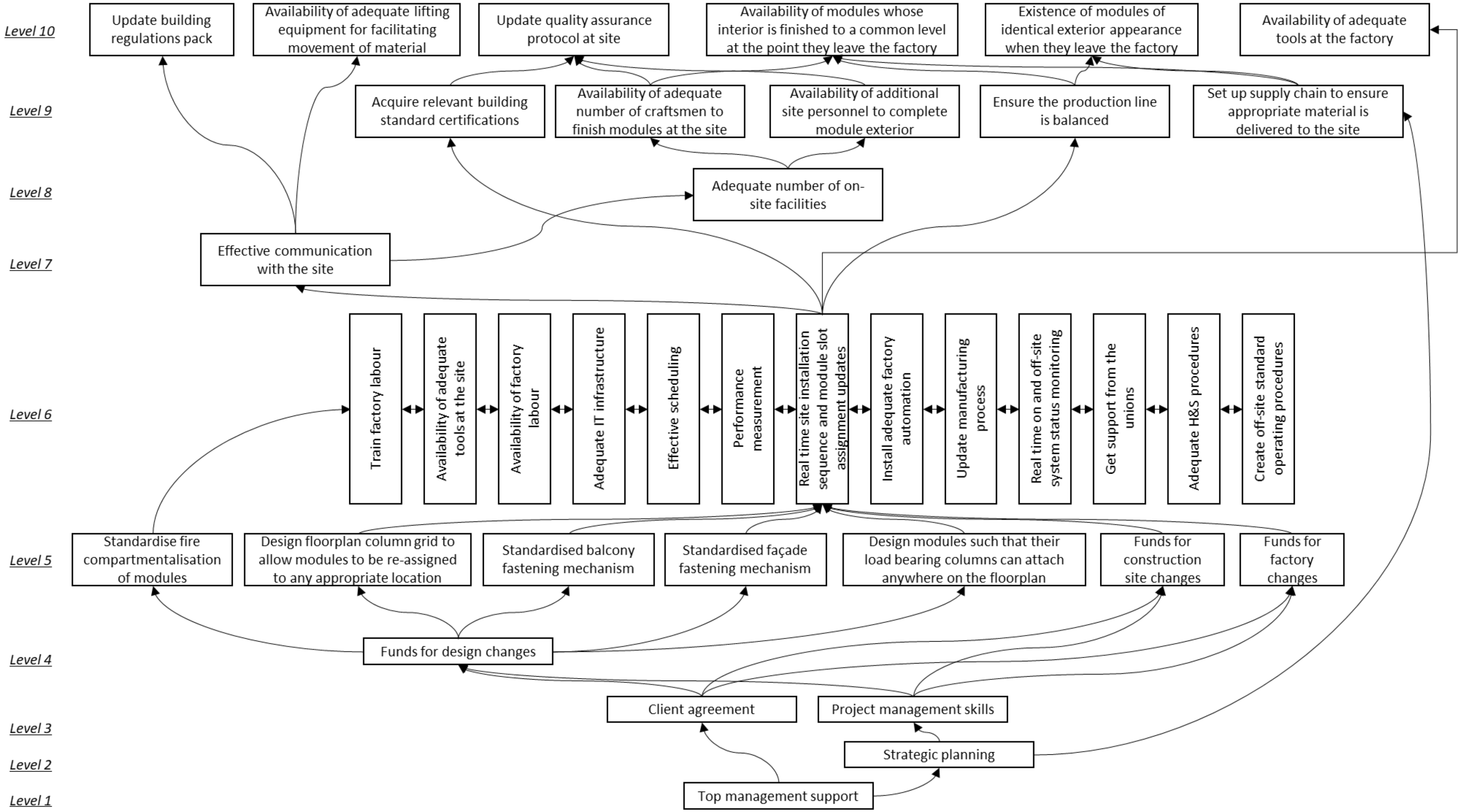

Figure B-4: Implementation roadmap for lateral assignment flexibility.

Appendix C

Appendix C pertains to Chapter 5.

C.1 Detailed evaluation of different modelling techniques

Recall from Section 5.4.1 the criteria defined to select a modelling technique:

<u>Criterion 1:</u> Reflect the operational behaviour of off-site construction systems by adequately capturing their constraints.

<u>Criterion 2:</u> Represent the uncertainty in the occurrence of random events such as whether a module is disrupted.

<u>Criterion 3:</u> Provide quantitative insight into the behaviour of off-site systems enabled by on-site installation flexibility in a reasonable computation time.

<u>Criterion 4:</u> Result in the selection of the (near-)optimal level of on-site installation flexibility weighed against alternative disruption management options.

Four potential categories of techniques for modelling the problem were identified: analytical, meta-heuristic, simulation-based, and simulation-based optimisation. An overview of each along with their benefits and drawbacks follows.

A wide range of analytical techniques has been used to model the behaviour of flexible supply chains. These are equation-based mathematical techniques, the most common of which are (non-) linear programs, both mixed integer and integer. Two common analytical formulations to tackle similar flexibility problems such as the above were found: capacity planning and scheduling problem formulations.

With respect to the former, linear programs have frequently been used to investigate the benefits of various types of flexibility (Jordan and Graves, 1995; Romero *et al.*, 2003; Tomlin, 2006; Ferrer-Nadal, Puigjaner and Guillén-Gosálbez, 2008; Kuzgunkaya and ElMaraghy, 2008; Hopp, Iravani and Xu, 2010). Capacity planning formulations incorporating flexibility decisions consist in determining: i) the quantity of products that are produced and transported across a supply chain, and ii) the optimal level of flexibility. The movements of individual elements (such as modules) within the supply chains are not modelled but rather the flow of their overall quantities in each time step (e.g. number of modules of type A transported in a day). The drawback of adopting this approach would be the inability to capture the on-site installation constraints (defined in Section 2.3.4) and hence it would not fulfil Criterion 1.

An alternative formulation which could fulfil Criterion 1 would be to frame the problem as a scheduling problem which is broadly concerned with sequencing jobs on machines. Additional extra decision variables could then be used to activate or relax constraints corresponding to the different types of flexibility. In this case, it could be envisaged to model the quality assurance bay, re-work stations, buffer storage bays, transport vehicles, and the crane as machines. The modules could be modelled as jobs to be processed by the machines. As there may be more than one re-work station, buffer storage bay, or transport vehicle, some machines may be modelled in parallel. This resembles the flexible flow shop scheduling problem, where there may be more than one machine that can complete an operation on a given job. There is ample literature on flexible flow shop scheduling problems (Lee and Loong, 2019). However, unlike typical flexible flow shop scheduling formulations where precedence constraints between operations are limited to those belonging to a particular job, the requirements of the on-site installation constraints mean that the operations have precedence constraints across operations on different jobs. More specifically, the crane installation operation for a given module may depend on the crane installation operation on other modules being completed beforehand, given that an upper floor module may not be installed until another module has been installed directly beneath it. To resolve this, similar mathematical constraints could be adopted from *concurrent shop* scheduling problem formulations, which deal with scheduling jobs with multiple subcomponents coming together (e.g. scheduling assembly lines). The reader is referred to (Maleki-Darounkolaei *et al.*, 2012; Komaki, Sheikh and Malakooti, 2019) for a more in-depth coverage of such formulations and a review of existing research. With respect to the remaining constraints, most are typical of analytical formulations of scheduling problems except for the blockage constraints. The latter have nonetheless been formulated mathematically in the past, for example, in (Hansmann, Rieger and Zimmermann, 2014) for a flexible flow shop and in (Maleki-Darounkolaei *et al.*, 2012) for a restricted case of a concurrent flow shop. It could therefore be feasible to fulfil Criterion 1 by formulating the problem analytically as a scheduling one given that the different constraints have previously been modelled successfully.

That said, analytical scheduling models may struggle to fulfil Criterion 2 given the difficulty in incorporating the uncertainty in whether a module is disrupted or not. One common approach is to use an expected processing time that factors in re-work time (Eskandari and Hosseinzadeh, 2014; Bootaki and Paydar, 2016). The problem with using such a probabilistic approach though is that it would not be able to reflect the on-site installation constraints accurately. What is more, most scheduling problems, even many of those that are deterministic and static, are NP-Hard or mathematically intractable (Sabuncuoglu and Goren, 2009). For instance, the problem of finding the minimum make-span schedule in a flow shop with more than two machines in a deterministic setting is NP-Complete and therefore computationally complex to solve when the number of jobs to process increases (Garey, Johnson and Sethi, 1976). The more complex formulations mentioned previously are therefore also likely to be NP-Hard (Hall and Sriskandarajah, 1996; Komaki, Sheikh and Malakooti, 2019). Consequently, solving the problem in a practically feasible time may prove to be difficult and hence Criterion 3 may not be achievable.

A second technique which would fulfil Criterion 3 is to use meta-heuristics to generate solutions to scheduling problems. They are capable of achieving (near-) optimal solutions in a much shorter time. A range of meta-heuristics has been used in the past, each with their own advantages and disadvantages. Particle swarm (PS) optimisation (Eberhart and Kennedy, 1995) is straightforward to use (Kuo and Rajendra Prasad, 2000) and can have a high convergence rate (Palupi Rini, Mariyam Shamsuddin and Sophiyati Yuhaniz, 2011) but may easily fall into local optima in a high dimension space (Zhu, 2010). Tabu search (TS) (Glover, 1986) avoids getting trapped in local optima but defining the search space memory structure is difficult given that it is very much problem-dependent (Kuo and Rajendra Prasad, 2000). Simulated annealing (SA) (Kirkpatrick, Gelatt and Vecchi, 1983) also avoids getting trapped in local optima and offers the possibility for parallel processing which speeds up computation times (Coello, Lamont and Veldhuizen, 2007) but it is difficult to define a good cooling schedule (i.e. the rate at which it converges to a solution) (Coello, Lamont and Veldhuizen, 2007). It also requires a large number of computations to resolve (Kuo and Rajendra Prasad, 2000). A genetic algorithm (GA) (Melanie, 1996) searches the global search space effectively, is useful for solving large discrete optimisation problems (Kuo and Rajendra Prasad, 2000) and does not require complex mathematical structures to be developed (Kuo and Rajendra Prasad, 2000). It also generates a solution to complex problems in a typically shorter time than other meta-heuristics (Sankar, Ponnanbalam and Rajendran, 2003), and as with simulated annealing offers the possibility of parallel processing. The downside of genetic algorithms is that it is difficult to determine their governing parameters as well as the objective function penalties that infeasible solutions must incur (Kuo and Rajendra Prasad, 2000). Nevertheless, despite the advantages of meta-heuristics over analytical methods to generate reasonable solutions to NP-Hard problems (thereby fulfilling Criterion 3), the fact that they still rely on the underlying mathematical formulation of the scheduling problem means that they also face similar difficulties as analytical methods to fulfil Criterion 2.

Developing a simulation-based technique to model the problem is another alternative that was considered. There is a range of different types of simulation techniques including Agent-Based Simulation, System Dynamic Simulation, and Discrete Event Simulation. The first is of particular use when there is a need to model the behaviour and decisions of different entities in a system (Kim and Kim, 2010), which is not the case for the problem at hand. The second is useful to model the causal relationships between different variables in complex and dynamic systems (Kim *et al.*, 2020), which again is not pertinent to this research problem. And whereas the second is more geared towards high level strategic questions (Tako and Robinson, 2012), the third, Discrete Event Simulation is useful to model operational and tactical decisions. It is well suited to representing complex stochastic supply chain systems (Osorio *et al.*, 2017). It has also been used extensively in modelling construction system behaviour (Martinez, 2009) including modular off-site construction systems (Alvanchi *et al.*, 2012; Goh and Goh, 2019). As such it is a promising simulation-based method to address the problem.

Simulation techniques offer several benefits over analytical and meta-heuristic based methods (Srivastava *et al.*, 1989). They do not require as many simplifying assumptions to model real world operations as standard mathematical methods (Juan *et al.*, 2014). For example, the uncertainty over whether a module might require re-work would not have to be simplified by factoring in re-work time into the expected processing time, as was the case for the previous two methods – hence making it feasible to fulfil Criterion 2. Furthermore, it is particularly well suited for cases where some factors are random variables that interact with each other and may be difficult to incorporate in a meaningful way in an analytical model (Srivastava *et al.*, 1989). It is also an accepted method to approach problems set in environments where there are many constraints (Ribas, Leisten and Framinan, 2010), which is certainly the case here. What is more, it scales better to larger problem instances (Juan *et al.*, 2014), meaning it is feasible to fulfil Criterion 3. In addition, it can be used to reinforce and facilitate managerial decision making processes, conduct experiments without disrupting system operation, and easily gain insight into different scenarios (Chou, Yang and Chong, 2009). However, the use of simulation does come with certain disadvantages. To begin with, it does not generate optimal solutions (albeit when problems are NP-Hard, mathematical models do not necessarily do so either), meaning by itself it cannot fulfil Criterion 4. What is more, the simulation model must be run multiple times, especially when there is an increasing number of input parameters, to achieve statistically significant results.

The three previously described methods for modelling the problem all have limitations in fulfilling the criteria. Simulation-Based Optimisation (SBO) techniques have been used to replicate complex real-world production environments and their constraints (Frantzén, Ng and Moore, 2011) and have been proven to be highly successful in doing so (Syberfeldt *et al.*, 2009). Broadly, SBO techniques combine an analytical or meta-heuristic technique, called the *optimiser*, with a simulation-based technique in the hope of overcoming their individual shortcomings (Diaz, Handl and Xu, 2018). The *simulation model* of the SBO serves to evaluate the performance of the system under a given set of conditions or parameter settings. The *optimiser*, which may be an analytical technique or meta-heuristic, identifies the (near-) optimal solution to the problem.

There are a number of ways in which the optimiser and the simulation model can interact to achieve a solution (Figueira and Almada-Lobo, 2014):

SBO Option 1: The simulation model can be set up as a black-box evaluation function for the optimiser.

SBO Option 2: The simulation model complements results generated by the optimiser either by:

a) obtaining more realistic performance values for a solution generated by an optimiser through simulation; or
b) iteratively converging to optimal values of performance.

SBO Option 3: The simulation model is used to estimate parameters of an analytical optimiser.

Each technique comes with its own advantages and disadvantages (Figueira and Almada-Lobo, 2014).

SBO Option 1 can be computationally expensive as it requires the simulation model to evaluate each candidate solution produced by the optimiser on top of the fact that the associated meta-heuristics are already more computationally intensive, as mentioned earlier. Nonetheless, such a technique provides an effective way to cover a very large search space.

SBO Option 2a) can be efficient but is only effective if the optimiser generates a sufficiently accurate solution which the simulation model can then use as a basis for a more accurate measure of performance. For example, consider the case where the optimiser determines the set of parameters which yield the optimal performance value. It could well be that even though this set of parameters outperforms all others, when uncertainty is incorporated through simulation, the distribution of the performance values overlaps significantly with at least one other set of parameters. Hence there is a risk that the method does not necessarily identify the one set of parameters which outperforms others. SBO Option 2b), where the optimiser and the simulation model iterate with the aim of converging to the optimal set of parameters may not be effective if there is a continuing large discrepancy between the results generated by each model.

SBO Option 3 is the most appropriate for this case. The simulation model would first be used to capture the complex behaviour of the system and its constraints (Criterion 1) as well as the uncertainty

(Criterion 2). It would then calculate the performance of each combination of flexibility and disruption management investment options. The values generated would subsequently be input into the analytical optimiser to select the best performing combination. One additional benefit is that it ensures that all feasible options for the decision maker have been evaluated. This technique is feasible as long as the number of different combinations of on-site installation flexibility with disruption management options is not too time consuming to simulate, otherwise then the SBO Option 1 may be the most appropriate.

To summarise, a range of different modelling techniques was evaluated. Each has its own advantages and disadvantages and is capable of at least partially fulfilling some of the modelling requirements. Some techniques, even though they are capable of fulfilling all the criteria, may not be the most appropriate formulation. The above discussion has been summarised in Table C.1. Ultimately, the modelling technique selected is to use simulation to estimate parameters of an analytical optimiser.

Table C.1: Summary of how the different modelling techniques fulfil the various criteria (Y = Yes, criterion met; (Y) = Potentially/partially met; N = No, criterion not met).

		Analytical		**Meta-heuristics**	**Simulation**			**Simulation-Based Optimisation**		
Criterion	**Shortened description of criterion**	Capacity planning formulation	Scheduling formulation	GA, SA, TS, PS	Agent-based Simulation	System Dynamic Simulation	Discrete Event Simulation	Simulation acts as black-box evaluator for optimiser	Simulation complements optimiser solution	Simulation estimates parameters for optimiser
1	**Models system behaviour accurately**	N	Y	Y	(Y)	N	Y	Y	Y	Y
2	**Models uncertainty**	N	N	N	Y	Y	Y	Y	Y	Y
3	**Reasonable computation time**	N	N	Y	Y	Y	Y	(Y)	(Y)	Y
4	**Selects best flexibility option & disruption management options**	Y	Y	Y	N	N	N	Y	Y	Y

C.2 The Discrete Event Simulation model

The DES software that was used to model the system was MATLAB R2018b SimEvents[14]. It was selected for several reasons:

[14] https://uk.mathworks.com/products/simevents/features.html

- It contains libraries of objects which can be used to model the modular off-site construction system described above and has been used in the past to model off-site systems (Salimi, Mawlana and Hammad, 2018)
- Importantly, it allows for custom control logic to be programmed into the various elements of the model to reflect the behaviour of the system accurately – most notably the logic governing the installation sequence.
- The simulation model can be called as part of an overall program which may include additional initialisation steps prior to running the model
- It provides a user-friendly interface which is beneficial when explaining the model to practitioners

A mapping of the elements of the modular off-site construction system onto their representation in the MATLAB DES model is given in Table C.2. The SimEvents elements that are used in the model to control the installation of modules at the site are indicated by an “x” in the “Control element” column.

In SimEvents, a module is modelled as an Entity. Each Entity was defined to have a set of attributes, which can be thought of as variables, to which data may be read from and written to by the various elements in which the Entity enters. Each Entity has a set of attributes as follows:

- ModuleID: is the unique module ID which is assigned to each module which exits the factory. It is primarily used by the simulation model to select the appropriate entity to be installed next by the crane.
- TypeID: stores the type of module. This is used by the simulation model elements to ensure that the right type of module is installed in a given slot.
- FactoryRework: stores whether a module requires re-work or not. This is used by the elements which route entities to the re-work bays.
- EntityPriority: the priority of a module determines the order in which events triggered by the entities are processed should two events triggered by different modules occur at the same timestep.
- FloorID: stores the floor on which a module is to be installed.
- SlotID: stores the ID of the slot in which the module is installed.
- SlotXCoord, SlotYCoord, SlotZCoord: respectively store the x, y, and z co-ordinate on the building floorplan of the slot in which the module is installed.
- FloorID, SlotID, SlotXCoord, SlotYCoord and SlotZCoord are used to update the model variables with the installation progress over time and help to determine which modules can be installed next by the crane.

Table C.2: Overview of how key elements of the modular off-site construction system map were modelled in MATLAB SimEvents.

Modular off-site construction system element/process	MATLAB SimEvents element	Control element	Comments
Modules	Entity		
Factory production line exit	Entity Generator		
Physical path modules can take between different elements of the system	Connector		
Split in the route a module can take	Entity Output Switch		Used to deviate modules towards the bays where re-work takes place. The “Switching criterion” of the block was set to “Attribute” so as to select only modules marked for re-work.
Merging of two routes a module could follow	Entity Input Switch		
Quality Assurance	Entity Server		
Re-work bays	Entity Server		
Transport	Entity Server		
Buffer	Entity Store		
Crane installation	Entity Server		
Site installation manager	Entity Gate	x	This element represents the site installation manager who selects which module will be installed next by the crane. The “operating mode” of the gate was set as a “Selection Gate” which only allows modules which have the correct TypeID through.
Information flow	Simulink Function	x	Custom elements made up of various elements such as the *Message Block* (to transmit information), *Data Store Read/Write* (to read/write variables shared across various other blocks), and *Constant Block* (to store initialisation variables).
	Data Store Block	x	Store data which is shared across various blocks
Modules successfully installed	Entity Terminator		

Figure C-1 shows a screenshot of the DES model with its primary elements and their interconnections. They were connected in such a way that the entity flow in the model reflects that of the modules in the problem description. The buffer’s Entity Store and the crane installation’s Entity Server blocks both have additional control scripts that are triggered when i) an entity enters and exits the block for the former and ii) when an installation process is completed by the latter. These scripts control which modules in the buffer are allowed to be installed next. The flow chart for each may be seen in Figure C-2.

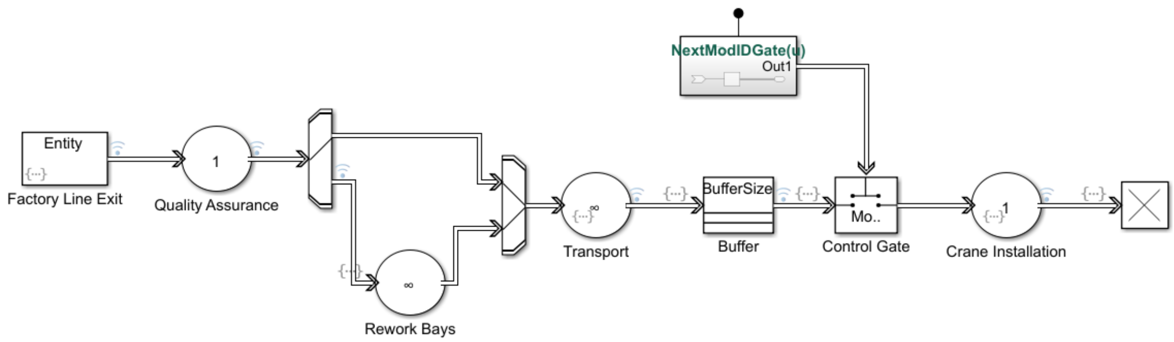

Figure C-1: Screenshot of the primary elements of the MATLAB Discrete Event Simulation model (N.B. not all elements related to the control of the module installation are shown here).

Because scripts are only triggered when an event occurs in MATLAB SimEvents, the decision regarding which module is to be installed next may be controlled by either the Buffer or the Crane Installation elements, depending on the system status. Should there be no modules left in the buffer after the crane has installed a module, the model is programmed so that the buffer element checks any new module which arrives and determines whether it is eligible to be installed. If it is, then the system lets it through to the Crane Installation element. When there is more than one viable module, then the crane lets the module with the highest priority through.

At the moment that the Crane Installation element completion script is deciding which module to install next, the system is unaware of modules that are about to arrive in the buffer. To accommodate the case where delayed modules arrive after the decision has been taken, the buffer entry script is set to check all delayed modules as they arrive and if appropriate, overwrite the decision made by the crane installation script.

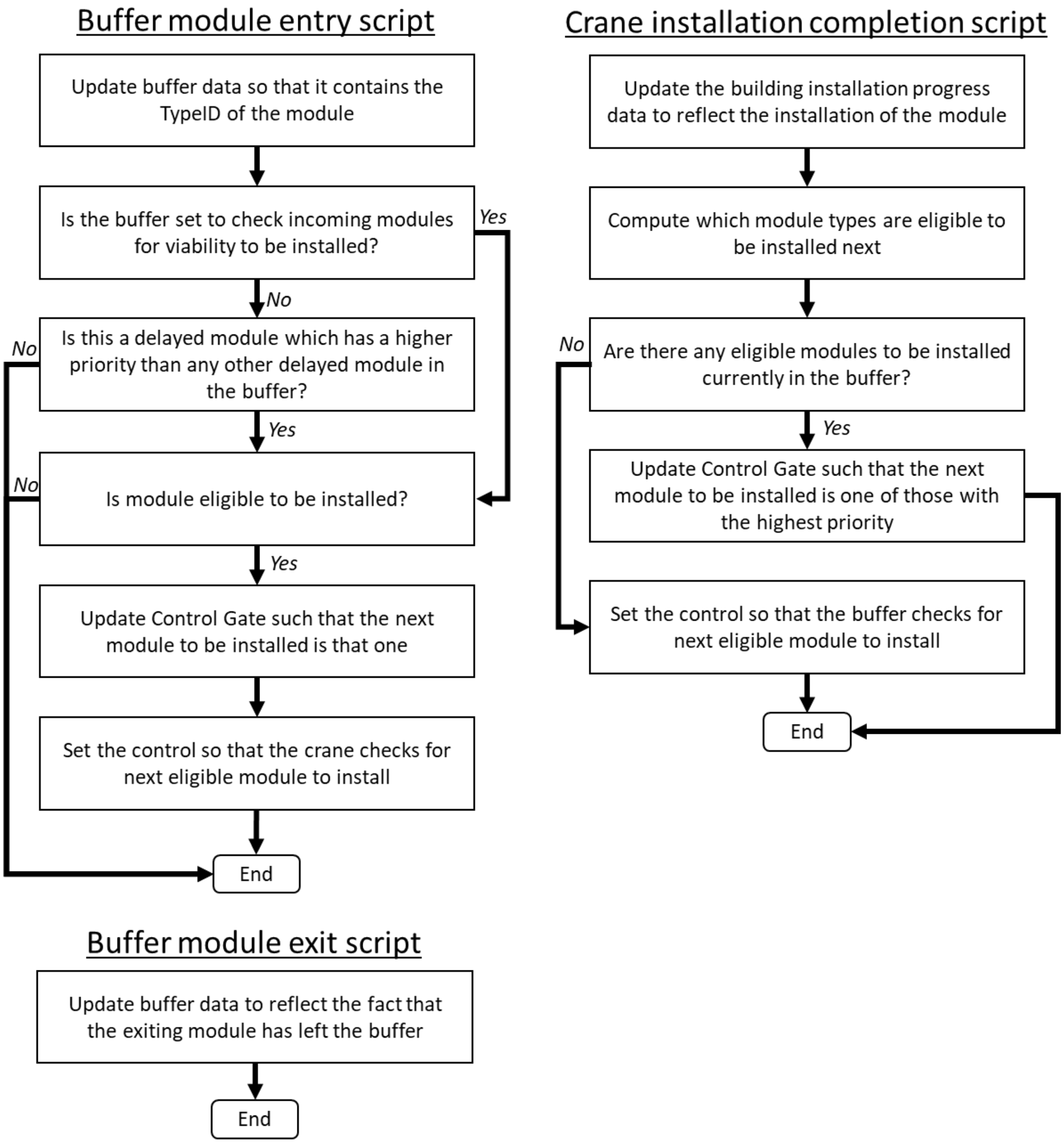

Figure C-2: Flow charts of some of the key scripts governing the module installation.

C.3 Cost saving calculation

Each cost saving is calculated as follows:

$$s_{ijkn} = C_{baseline\_n} - C_{ijkn}$$

$C_{baseline\_n}$ is the cost owing to disruptions of replication n when no investments in on-site installation flexibility, disruption mitigation improvement, or permanent storage buffer are made:

$$C_{baseline\_n} = C_{em\_storage_{baseline\_n}} + C_{rework_{baseline\_n}} + C_{delay_{baseline\_n}}$$

where $C_{em\_storage_{baseline\_n}}$ is the cost of storing modules in an emergency buffer, $C_{rework_{baseline\_n}}$ is the re-work cost, and $C_{delay_{baseline\_n}}$ is the cost incurred as a result of any delay.

C_{ijkn} is the sum of the cost of investments in disruption mitigation options plus the cost owing to disruptions. The investment costs include: the cost of the disruption mitigation improvement option i, C_{imp_i}; the cost of on-site installation flexibility combination $j, C_{flexcomb_j}$; the fixed cost of having a permanent storage buffer of a given size $C_{fixed\_perm\_storage_k}$; and the variable cost involved in operating the permanent storage buffer for the duration of the installation phase, $C_{var\_perm\_storage_{ijkn}}$. The disruption costs include the cost of storing modules in an emergency buffer, $C_{em\_storage_{ijkn}}$; the re-work cost, $C_{rework_{ijkn}}$; and the cost incurred as a result of any delay, $C_{delay_{ijkn}}$. Hence:

$$C_{ijkn} = C_{imp_i} + C_{flexcomb_j} + C_{fixed\_perm\_storage_k} + C_{var\_perm\_storage_{ijkn}} + C_{em\_storage_{ijkn}} + C_{rework_{ijkn}} + C_{delay_{ijkn}}$$

Using the data collected from experts in Table 5.1, the various $C_{var\_perm\_storage}$, $C_{em\_storage}$, C_{rework}, and C_{delay} costs are calculated as follows:

$$C_{var\_perm\_storage_X} = C_{var\_perm\_storage\_per\_time\_unit} \times TPIT_X$$

$$C_{em\_storage_X} = C_{em\_storage\_per\_module\_time\_unit} \times TEST_X$$

$$C_{rework_X} = C_{rework\_per\_time\_unit} \times TRT_X$$

$$C_{delay_X} = C_{delay\_per\_time\_unit} \times DELAY_X$$

Where X is either $ijkn$ or $baseline\_n$, $TPIT_X$ is the total project installation time, $TEST_X$ is the total time modules were stored in the emergency storage buffer, TRT_X is the total time spent on re-work, and $DELAY_X$ is the total installation phase delay. $TPIT_X$, $TEST_X$, TRT_X, and $DELAY_X$ are output directly from the DES model.

Appendix D

Appendix D pertains to Chapter 6.

D.1 Case study B

D.1.1 Further explanation of behaviour

The behaviour observed in Figure 6-18 can be explained by the effects of disruption duration and probability of disruption. Each is explored in turn starting with the effect of disruption duration.

At any given disruption probability, the mean percentage reduction in installation time improved as disruption duration increased. This is because the longer the duration, the more scope there was for flexibility to make up the delay. That said, if a module were to be disrupted too close to the end of the slot installation sequence, all other modules would be installed before it arrived at the site and the delay would start to build up. The longer the disruption duration, the more slots at the end of the installation sequence were susceptible to this risk (see Table 6.4 and its accompanying explanation). As a result, the sensitivity of the mean percentage reduction in installation time reduced with increasing disruption duration (i.e. at a given probability of disruption, the contours are more tightly packed for short disruption durations than for longer ones).

The behaviour as the probability of disruption fell below line A can in part be explained by the fact that there was an increasing chance that no disruption occurred in some of the replications. Hence, the reduction in installation time – even though flexibility was enabled – for those replications was zero. Thus, the mean installation time reduction is lower than in cases where the disruption probability is greater. As the probability of disruption increased above line A, it was more likely that modules destined for the last slots of the building were disrupted. For these slots, the full benefits of flexibility are not felt – if at all. This is because even though flexibility may allow installation to continue, the installation phase cannot finish until the disrupted module arrives (again, see Table 6.4 and its accompanying explanation). Consequently, the benefit of on-site installation flexibility diminished in terms of mean percentage reduction in installation time as the probability of disruption increased above line A. Finally, the sensitivity of the mean percentage reduction in installation time to probability of disruption was greater at high disruption durations than at low. This is because it is more likely that there will be a disruption occurring for modules intended for slots at the end of the installation sequence mentioned earlier.

D.1.2 Cost estimates of flexibility enablers

Table D.1: Estimates of costs for each enabler in Case Study B. Green = Yes; Red =No.

Enabler	Enabler required?						Cost of enabler (£)						Cost once if required?	Comment
	Installation sequence		Slot assignment				Installation sequence		Slot assignment					
	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)		
Update quality assurance protocol at site	Green	Green	Green	Green	Green	Green	200	200	200	200	200	200	Y	£25/t.u. x 40 t.u. of work for engineer; depreciated over 5 projects.
Availability of additional site personnel to install modules	Green	Red	Red	Red	Red	Red	2964						N	Unskilled worker £11/ t.u.; £15/ t.u. skilled; project length 114 t.u. max.
Availability of additional site personnel to complete module exterior	Red	Red	Green	Green	Green	Green							N	Exterior is identical.
Availability of adequate number of craftsmen to finish modules at the site	Red	Red	Green	Green	Green	Green							N	Lateral option 2: decide to only produce DL. Lateral option 3: only produce DL and DR. Because changes are made at the factory level, there is no additional work required at the site.

Enabler	Enabler required?						Cost of enabler (£)						Cost once if required?	Comment
	Installation sequence		Slot assignment				Installation sequence		Slot assignment					
	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)		
Availability of adequate lifting equipment for facilitating movement of material													Y	Can manage with what was already planned.
Adequate number of on-site facilities													Y	Capable of managing with those already on site.
Availability of adequate tools at the site													N	Capable of managing with those already on site.
Create on-site standard operating procedures							200	200					Y	£25/ t.u. x 40 t.u. of work for engineer; depreciated over 5 projects.
Train site personnel with new methods of installation							18.75	18.75					Y	1 t.u. meeting: £25/ t.u. manager, 10x £13.5/ t.u. (5 skilled 5 unskilled) depreciated over 20 projects.
Jump crane to height capable of reaching all areas of the building from start of project													N	Install crane at max height. No need to change anything, but it is necessary to organise to do it.

Enabler	Enabler required?						Cost of enabler (£)						Cost once if required?	Comment
	Installation sequence		Slot assignment				Installation sequence		Slot assignment					
	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)		
Erect temporary works to support the crane							132						N	4h x 3 unskilled £11 / t.u.
Availability of cranes with adequate span from start of build													N	No cost
Availability of crane with adequate lifting strength													N	No cost
Accurate crane path control													Y	No cost
Alter module connector design								400					N	£25/ t.u. x 2 engineers x 40 t.u. depreciated over 5 projects.
Re-design load bearing portions of the modules such that they are capable of withstanding lateral loading imbalances							2000	2000					Y	£25/ t.u. x 2 engineers x 40 t.u.

Enabler	Enabler required?						Cost of enabler (£)						Cost once if required?	Comment
	Installation sequence		Slot assignment				Installation sequence		Slot assignment					
	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)		
Design "safety walkway" to cover empty slots							600						N	£25/ t.u. x 3 engineers x 40 t.u. depreciated over 5 projects.
Standardise fire compartmenta-lisation of modules									2000	2000	2000	2000	Y	£25/ t.u. x 2 engineers x 40 t.u.
Standardise module structures									2000				N	£25/ t.u. x 2 engineers x 40 t.u.
Strengthen building foundations									2000				N	£25/ t.u. x 2 engineers x 40 t.u.
Design floorplan column grid to allow modules to be re-assigned to any appropriate location									2000	2000	2000	2000	Y	£25/ t.u. x 2 engineers x 40 t.u.
Design sufficient spacing between modules							400	400					Y	£25/ t.u. x 2 engineers x 40 t.u.

Enabler	Enabler required?						Cost of enabler (£)						Cost once if required?	Comment
	Installation sequence		Slot assignment				Installation sequence		Slot assignment					
	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)		
Increase the range of acceptable installation tolerances							400	400					Y	£25/ t.u. x 2 engineers x 20 t.u.
Standardised balcony fastening mechanism													Y	No cost. No balconies.
Standardised façade fastening mechanism													Y	No cost. All same façade.
Design modules such that their load bearing columns can attach anywhere on the floorplan													Y	No need.
Create off-site standard operating procedures							50	50	50	50	50	50	Y	£25/ t.u. x 40 t.u. of work for engineer; depreciated over 20 projects.
Update manufacturing process							500	500	500	500	500	500	Y	£25/ t.u. x 2 engineers x 10tu. No significant changes are required.

Enabler	Enabler required?						Cost of enabler (£)						Cost once if required?	Comment
	Installation sequence		Slot assignment				Installation sequence		Slot assignment					
	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)		
Install adequate factory automation													Y	No need.
Train factory labour													Y	No need.
Availability of factory labour													Y	No need.
Availability of adequate tools at the factory													Y	No need.
Ensure the production line is balanced							500	500	500	500	500	500	Y	£25/ t.u. x 2 engineers x 10tu. Just need to lightly rebalance if at all.
Availability of modules whose interior is finished to a common level at the point they leave the factory													Y	Process accomplishes this. No postponement required either.
Existence of modules of identical exterior appearance when they leave the factory													Y	Process accomplishes this. No postponement required either.

Enabler	Enabler required?						Cost of enabler (£)						Cost once if required?	Comment
	Installation sequence		Slot assignment				Installation sequence		Slot assignment					
	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)		
Funds for construction site changes													Y	NA
Funds for factory changes													Y	NA
Funds for design changes													Y	NA
Real time site installation sequence and module slot assignment updates													Y	Existing IT and communication system capable of this already.
Adequate IT infrastructure													Y	Existing IT and communication system capable of this already.
Real time on- and off-site system status monitoring													Y	Existing IT and communication system capable of this already.
Update building regulations pack									400	400	400	400	Y	£25/ t.u. x 1 engineers x 16 t.u.

Enabler	Enabler required?						Cost of enabler (£)						Cost once if required?	Comment
	Installation sequence		Slot assignment				Installation sequence		Slot assignment					
	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)		
Acquire relevant building standard certifications							100	100	600	600	600	600	Y	It is assumed that the building standard warrant will be an amendment (they would have paid most of it anyway). The assignment flexibility is more expensive than that of the sequence flexibility as in the former more significant changes to the module design may be made.
Adequate H&S procedures							400	400	400	400	400	400	Y	£25/ t.u. x 1 HS manager x 16 t.u. . Just need to lightly rebalance if at all.
Permission to build on all areas of the construction site from the start of the project													N	Can be granted.
Top management support													Y	No additional cost.
Effective communication with the site													Y	No additional cost.
Client agreement													Y	No additional cost.
Strategic planning													Y	No additional cost.

Enabler	Enabler required?						Cost of enabler (£)						Cost once if required?	Comment
	Installation sequence		Slot assignment				Installation sequence		Slot assignment					
	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)	Vertical	Lateral	Vertical	Lateral option 1 (4 module types)	Lateral option 2 (3 module types)	Lateral option 3 (2 module types)		
Project management skills													Y	No additional cost.
Effective scheduling													Y	No additional cost.
Performance measurement													Y	No additional cost.
Get support from the unions													Y	Very low chance of opposition.
Set up supply chain logistics for module design changes													Y	Not needed for design changes.
Set up supply chain for "safety walkway" production							2000						N	£1000 per walkway x 10 walkways / depreciated over 5 projects.
Set up supply chain to ensure appropriate material is delivered to the site													Y	Can be handled in-house at no extra cost (e.g. by placing in modules destined to site). No postponement anyway.

D.1.3 Permanent buffer costs

Table D.2: Costs for permanent buffer of different capacities.

Capacity (# modules)	Cost of buffer land (£)
0	0.00
1	273.28
2	546.55
3	819.83
4	1093.10
5	1366.38
6	1639.65
7	1912.93
8	2186.20
9	2459.48
10	2732.75
11	3006.03
12	3279.30
13	3552.58
14	3825.85
15	4099.13
16	4372.40
17	4645.68
18	4918.95
19	5192.23
20	5465.50
21	5738.78
22	6012.06
23	6285.33
24	6558.61